THE

RAY SOCIETY

INSTITUTED MDCCCXLIV

This volume (No. 130 of the Series) is issued to the Subscribers to the RAY SOCIETY *for the Two Years* 1942 *and* 1943.

LONDON

MCMXLV

THE PLEISTOCENE PERIOD

ITS CLIMATE, CHRONOLOGY AND FAUNAL SUCCESSIONS

BY

FREDERICK E. ZEUNER, D.Sc., F.Z.S., F.G.S.

LONDON

PRINTED FOR THE RAY SOCIETY

SOLD BY

BERNARD QUARITCH, LTD.

11, GRAFTON STREET, NEW BOND STREET, LONDON, W. 1

1945

Made and printed in Great Britain by
Adlard & Son, Ltd.,
at their works, Bartholomew Press, Dorking.

PREFACE

THE present work is the result of studies bearing on the chronology of the last million years, carried out at the Institute of Archæology in the University of London. It embodies the subject-matter of several courses of lectures, though the material has been re-arranged and the evidence greatly elaborated. After an initial attempt to cope in a single publication with both the evidence for the time-scales and their significance for archæology, anthropology and problems of evolution, it was found necessary to divorce the geological evidence from its archæological implications in order to make it quite clear that the chronology of the Pleistocene is not the hybrid product of geological and archæological considerations, but a system that stands or falls by itself. For this reason, however, the chronology of the Pleistocene, and the enormous amount of information concerning environment which is connected with it, gains in applicability. It becomes a kind of calendar which can be used in the dating of fossils, both animal and human, and of prehistoric industries, as well as the natural background for the history of life in the past. The present book, therefore, does not contain references to archæological aspects of the matter—these have been treated in a separate publication (*Dating the Past*, Methuen, London, 1945)—but is entirely concerned with the evidence for the relative and absolute chronology of the Pleistocene, for the various types of environment existing at certain times in certain areas, and with the evolution of the fauna found in deposits of known age. Thus, it forms the essential basis for the conclusions arrived at in the second publication, *Dating the Past*.

This book owes its final form to so many hands that I could not call it mine without acknowledging my debt to all those friends, colleagues and institutions whose help and advice I have enjoyed, though their number is too great to name them all. My special gratitude is due to those who have taken the trouble to read the entire manuscript; first and foremost to Mr. Day Kimball, with whom the entire matter has been discussed, and to whose superior logical powers I owe a great deal. Professor P. G. H. Boswell and Dr. W. T. Calman also had the kindness to read the complete manuscript and to suggest numerous improvements. Some chapters were read by Miss D. M. A. Bate and by Mr. D. L. Edwards, Director of the Norman Lockyer Observatory. The kindly and helpful criticism which I have received from these scholars has been of great benefit, and I wish to express my deep gratitude to all of them.

I further wish to acknowledge my indebtedness to the Trustees of the Leverhulme Studentship of the London Museum, under whose auspices part of the research has been carried out, to the Department of Geology of the British Museum (Natural History) for hospitality in difficult times, and to

the Council of the Ray Society for undertaking the publication. The London University Institute of Archæology enabled me to study sections in Italy and France in 1937, and I derived great benefit from investigations carried out in the Channel Islands on the invitation of the Société Jersiaise in 1938. Observations made in Silesia, Poland and Czechoslovakia in 1932, when travelling with a grant from the Freiburger Wissenschaftliche Gesellschaft, have been incorporated also. Permission to use published illustrations was kindly given by the Councils of the Geological Society of London, the Geologists' Association and the Royal Anthropological Institute.

It is further a pleasure to tender my cordial thanks to those friends who have conducted me on many excursions, more especially to Drs. R. R. Marett and A. E. Mourant, and Père C. Burdo in Jersey, Professor H. Breuil and Mr. Harper Kelley in France, Professors G. A. and A. C. Blanc in Italy, Dr. E. Scherf in Hungary, and to Professors B. Zaborski and L. Knopp in Poland. Professor L. S. Davidaschvili in Moscow most kindly sent me important Russian papers and serial publications.

Finally, I should emphasize that a great many other helpers have, directly or indirectly, contributed towards the completion and shaping of this book. I am well aware that a work of this kind is, and cannot be but, the outcome of continued discussion of material and problems with expert friends, and to them as well as those named above I owe much of what is valuable in this book though, of course, I am alone responsible for the views expressed.

Department of Geochronology,
London University Institute of Archæology,
Inner Circle, Regent's Park,
London, W.C. 1.
December, 1944.

CONTENTS

CHAPTER IV. THE PLEISTOCENE CHRONOLOGY OF THE BRITISH ISLES.

CHAPTER V. THE ASTRONOMICAL THEORY AS THE BASIS OF AN ABSOLUTE CHRONOLOGY OF THE PLEISTOCENE.

CHAPTER VI. THE ABSOLUTE CHRONOLOGY OF THE PLEISTOCENE.

CHAPTER VII. CLIMATIC PHASES OF THE UPPER PLEISTOCENE IN THE COUNTRIES AROUND THE MEDITERRANEAN SEA.

CHAPTER X. FAUNAL EVOLUTION IN THE PLEISTOCENE.

INTRODUCTION

One of the neglected spheres of biological research is the history of the Recent fauna. Although there is plenty of provision for the study of the existing types of life in zoology, and for the study of extinct forms of the Tertiary and earlier periods in palaeontology, the fauna of the Quaternary (i.e. the Pleistocene or Ice-Age and the Holocene or Postglacial) has attracted relatively few workers. This is in part due to the fact that, the remains often being poorly preserved, this fauna offers little attraction to the zoologist; on the other hand, most of the species being still living, the palaeontologist is apt to despise them.

Yet it is from this Quaternary fauna that our Recent fauna has evolved, and this alone should be sufficient justification for the study of the most immediate ancestors of the Recent species. The differences detected may be small; they rarely exceed quantitatively the differences found to distinguish Recent species from each other. But this precisely offers an opportunity of studying changes of specific characters. I am convinced that a thorough investigation of the Pleistocene fauna will, in the long run, provide most valuable information concerning the evolution of new species.

Any such investigation, however, requires a background of historical data of three kinds, namely (*a*) environmental, (*b*) geographical, and (*c*) chronological. The natural changes in the environment of a Recent species are so slow that this environment can be regarded as stable. This is not so if a longer space of time, such as the Quaternary, is considered, and it is necessary to investigate the nature of environments and their climates, which existed at successive times in various places. Furthermore, the distribution of land and sea, which may be regarded as constant for the purpose of studying the living fauna, is the result of manifold changes in the course of longer periods of time, so that it is necessary to obtain information about geographical changes, such as the outlines of coasts, the height of the sea-level at certain times, changes of altitude, and so on.

The environmental and geographical data provide a sequence of events which is used to assign to the fossils found in the deposits a relative age. It is essential to have a system of relative chronology if it is intended to study changes in the course of time. Though the time cannot often be assessed in years, it is most important to know which form of life is the older and which the younger. The numerous fluctuations of the climate in the course of the Quaternary afford an admirable framework for such a relative time-scale, which is indispensable if the history of species is to be investigated. The well-known palaeontological method of dating strata by the fossils contained in them breaks down almost entirely in the Quaternary, since the total duration of this period was too short to result in the extinction or appearance of many well-characterized species.

Moreover, local survival plays an important part in the Quaternary.

If one adopted, for instance, *Hippopotamus amphibius* as a guide fossil, one might consider as contemporaneous a fauna of the First Interglacial of the Rhine Valley, a fauna of the Third Interglacial of the Thames Valley, a prehistoric fauna from the Nile Valley, and the Recent fauna of the Sudan. Clearly, then, the relative time-scale required for the study of the fauna has to be worked out on geological evidence only, taking into consideration fluctuations of climate and changes of a geographical character.

Finally, the question arises whether the relative time-scale established in this way can be made more useful by its interpretation in terms of absolute time. Even if such absolute time-scale be tentative and vague, it is bound to provide some concrete notion of the time required in the evolution of species. Two methods of measuring absolute time within the Quaternary have been developed and their results are consistent with one another.

The present book is chiefly concerned with providing the historical background for the evolution of the modern fauna, including man. It gives the evidence for climatic changes which took place in the course of the recent past, discusses the types of environment that existed at various times and places, and attempts to reconstruct the climatic zonation of Europe during the glacial phases. The stratigraphical evidence is used in building up a relative chronology, and a discussion of the absolute chronology which can be used in supplementing the relative one completes the "calendar" into which the faunal history has to be fitted.

Numerous references to the fauna will be found throughout the book, though these are chiefly confined to mammals and mollusca, the only two groups of the Quaternary fauna which have been investigated to some extent. In Chapter X, a number of faunal lists, both from the British Isles and from the Continent, are given in chronological order. They will provide some idea of the faunal changes and of the disappearance and appearance of species, subspecies and environmental types in the course of the last million years.

It is hoped that the material contained in this book may convince some workers of the urgency of historical research on the evolution of the modern fauna and may encourage them to take up this promising line.

CHAPTER I

SOME PRINCIPLES OF PLEISTOCENE STRATIGRAPHY

A. INTRODUCTION.

PRIORITY OF GEOLOGICAL DATING.—The Pleistocene, being a short and very recent geological period, suffers to a great extent from a lack of fossils suitable as chronological guides. In the earlier periods, fossils supply most valuable evidence of the relative ages of strata, and deposits containing a similar fauna in geographically separated districts can be regarded as approximately of the same age. In the Pleistocene, however, this palæontological method of dating meets with a very limited success, and it is not surprising that the ardent desire of finding some chronological guide has induced some workers to use the various Palæolithic industries as such. In other words, instead of determining the ages of the various phases of human evolution relative to the geological chronology, and establishing at which moment of the relative time-scale certain changes in the industrial and physical evolution of man took place, the practice was adopted of assuming that the sequence of human industries was well enough known to be used for the dating of geological deposits. The result of this reversal was a regrettable muddle which is being overcome only gradually.

In order to rule out any chance of applying archæological conceptions in the establishment of a Pleistocene chronology, no reference is made in the present book to the archæological contents of the deposits, except incidentally. This, in fact, is the only reliable way of obtaining a clear picture of the climatic phases of the Pleistocene and of their sequence. Moreover, it is the only sound way of arriving at an absolute chronology in years, as will be seen later.*

LOCAL CHARACTER OF PLEISTOCENE SECTIONS.—In adopting purely geological methods for dating in the Pleistocene, one is at once confronted by the very difficulty which has made many workers prefer the easier archæological method. This is the local character of many sections. Pre-Pleistocene strata are predominantly of marine origin and retain their characters over comparatively wide areas. Where they are of terrestrial origin, the difficulty of precise dating and correlating is just the same as in the Pleistocene. As an example, the deposits of the Triassic period of extra-Mediterranean Europe may be referred to.

If one imagines the present surface of, say, England to be fossilized and only observable here and there in geological sections, it becomes evident

* Note that the stratigraphical succession, or the sequence of climatic phases, constitutes the *relative* chronology, which is independent of any time-scale in years. The Chapters II to IV are concerned only with the *relative* chronology of the Pleistocene. The *absolute* chronology, depending on the application to the relative chronology of time-scales in years, is discussed separately in Chapters V and VI.

how difficult correct correlating of terrestrial deposits is. River gravels in one place, hill-wash in a second, weathering loam in a third, lake sediments in a fourth, would all be of the same age, and fossils would hardly help to prove this.

The implication concerning Pleistocene sections is that *any exposure* in a pit, quarry, etc., *which does not afford some unambiguous stratigraphical clue to its age, cannot be used for the purpose of constructing a Pleistocene chronology*. In any other geological period this would go without saying but, unfortunately, far too many chronological conclusions have been built on this kind of section in the Pleistocene. Thus, at least 999 out of a thousand Pleistocene sections, though perhaps of great local interest, are of no value in reconstructing the stratigraphical sequence.

Type of Evidence on which Pleistocene Stratigraphy should Rely.—The subdivisions of the periods previous to the Pleistocene are defined by changes in the fauna, but those of the Pleistocene are primarily based on changes of the climate. It is necessary, therefore, to find in the sections evidence for such climatic changes. They are provided chiefly by the presence of (*a*) moraines or other deposits of the ice, (*b*) loess, (*c*) frost soils and solifluction deposits, (*d*) weathering horizons, (*e*) travertines, (*f*) gravel terraces, and (*g*) certain types of fauna. The following introduction to this evidence for climatic changes during the Pleistocene is inevitably very short, but references are given to more comprehensive publications.

B. MORAINES.

Terminal Moraines.—The most obvious evidence for a climate different from that of to-day is the presence of moraines in an unglaciated area. *Moraines* are accumulations of detritus taken up, transported and laid down by glaciers. The term is used for the material itself as well as for the surface features built up. Thus a wall of debris and mud laid down along the front of a glacier, often partly washed by meltwater and compressed and contorted by oscillatory advances of the ice into it, is called an *end-moraine* or *terminal moraine*. Where a glacier fills the bottom of a valley *lateral moraines* are developed along the sides.*

Bottom Moraines.—Geologically more important, because often covering immense areas, is the *bottom-* or *ground-moraine*, the lining of the glacier's bed. In its lower portion it is the product of the friction between the ice and the ground below; it acts as a lubricant while the ice is active (bottom moraine proper). On rising ground it sometimes attains great thickness, and contortions show how the ground below was worked up by the ice and incorporated in the movement ("contorted drift," Fig. 1).

The upper portion is made up chiefly of material thawed out from inside the body of the ice. It is usually termed bottom-moraine also, though *englacial moraine* would be a more correct expression. As a geological deposit it is called *till*† or *boulder-clay*, because of the frequent presence of pebbles and boulders. It is nearly always unstratified.

* Introductions to glaciology: Geikie, 1894; Hess, 1904. A recent Arctic country, Spitsbergen, is monographed in Knothe, 1931. Important papers on moraines: Gripp, 1929; Slater, 1926, 1927; Gripp and Todtmann, 1926.

† This term is used chiefly in North America, and for pre-Pleistocene moraines.

The surface features of bottom-moraines left behind by melting ice vary according to whether the ice was in motion while melting down (in this case a more or less even surface is formed, with pits where lumps of ice were

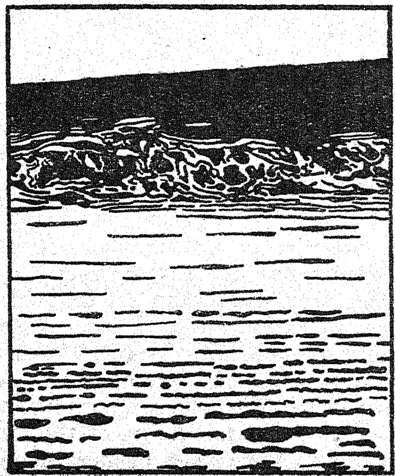


FIG. 1.—Bottom moraine (black) on glacifluvial sands. The lower portion of the moraine is intensely contorted, consisting of sand and clay. The contortions are drawn out towards the left, i.e. in the direction of the ice-movement. Upper portion of moraine is ordinary boulder clay. Total height of section, 24 ft. Weichsel Glaciation, Glienicke (Nordbahn), near Berlin, Germany.

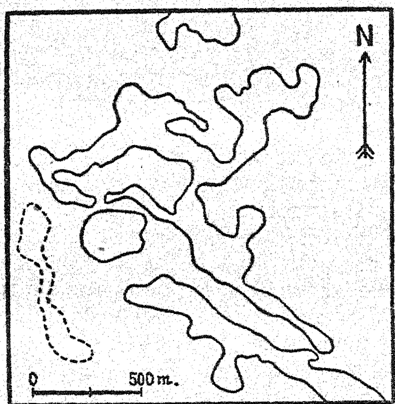


FIG. 2.—Portion of a dead-ice area. The system of crevasses in the ice is reproduced by the morainic deposits left behind. Full line: 200 m.-contour; broken line: 195 m.-contour, the latter surrounding a depression. From Psychod, Upper Silesia. (Zeuner, 1934c.)

enclosed), or whether the ice became motionless before finally melting down (*dead ice*). In the latter case, the network of crevasses often is clearly reproduced by the surface of the morainic deposits (Fig. 2).

The presence of a bed of boulder clay or of contorted drift in a section clearly proves that ice had at one time invaded the area. If there are two beds of bottom-moraine, however, the intervening layer requires careful study. If it can be shown that the climate was mild while this layer was forming (weathering, fauna or flora might help to establish this), then the two bottom-moraines represent two distinct cold phases. If not, then they may or may not be evidence of distinct glacial phases. It is possible, for instance, that a bed of sand between two boulder-clays was formed by "englacial" water running in a cavity inside the body of the ice.

c. LOESS.

Loess.—Another most important climatic deposit is *loess*, wind-blown dust which is finer than sand, but coarser than clay. Loess is found in Europe chiefly in a belt stretching from south England and north France to South Russia and adjacent Asia. Large areas in China, and also in North America, are covered with loess. The origin of loess (Soergel, 1919; Grahmann, 1932)—disputed for many years—is now well established, as will be shown presently. The climatic conditions associated with the deposition of loess were, and are, fairly dry, of the steppe type. In Europe the temperature was low in the phases of loess deposition (Zeuner, 1934*a*, 1937), but this need not apply to other loess regions. The considerations which follow, therefore, are valid for Europe only.

Mechanical Analysis of Loess.—The æolian nature of loess (Fig. 3, D) is most easily shown by comparing it with modern wind-blown dusts (Fig. 3, A and C). In order to identify wind-blown dust, the material is separated into a series of grades of coarseness of the grains composing it, by a washing process called "mechanical analysis" (see, for instance, Zeuner, 1938). Wind-blown dust is largely composed of grains between 0·1 and 0·01 mm. diameter (the "*silt* grade"), with very little coarser material and an amount of very fine (loamy or clayey) matter varying with the degree of weathering suffered by the specimen.

This constancy in the composition of loess is a very curious fact. It affords a subtle means of recognizing loess and allied wind-borne sediments. Water-borne sediments, even if they are roughly of the same average grade and outwardly resemble loess (as do many silts, for instance, fig. 3, F), never exhibit this concentration within the limits of 0·1 and 0·01 mm., unless, of course, they are made up of derived loess transported by water. On the other hand, even wind-borne deposits of an age much earlier than Pleistocene can be recognized by mechanical analysis (Fig. 3, E).

Causes of the Uniformity of Loess Grading.—The cause of this uniformity in the grading of wind-borne deposits is probably twofold. Whether the dust was picked up in hot deserts, or temperate deserts, or arctic regions, or in the regions of moraines and glacifluvial sands surrounding the Pleistocene ice-sheets, or from the gravels of rivers and on slopes of mountains which were under the refrigerating influence of an ice-sheet (*periglacial climate*), the source of the dust was always an area with a comparatively dry climate.* In such dry regions, chemical weathering of the

* Frost climates may be classified as dry, since the water is solid during the major part of the year.

rocks is superseded by mechanical weathering, which breaks down the rock either by repeated intense heating by day and cooling at night, causing alternating expansion and contraction (*insolation weathering*), or by repeated freezing which causes the freezing water in the cracks to expand, thus widening them (*frost weathering*). The result is the well-known rock-waste of the deserts, high mountains and arctic regions. The process of mechanical disintegration may continue until the size of the particles has become so small that the movements caused within them by insolation or frost are compensated by the elasticity of the material. It seems that, for the majority of rocks, this limit lies between a tenth and a hundredth of a millimetre. This is probably the reason why large quantities of dust grains of this

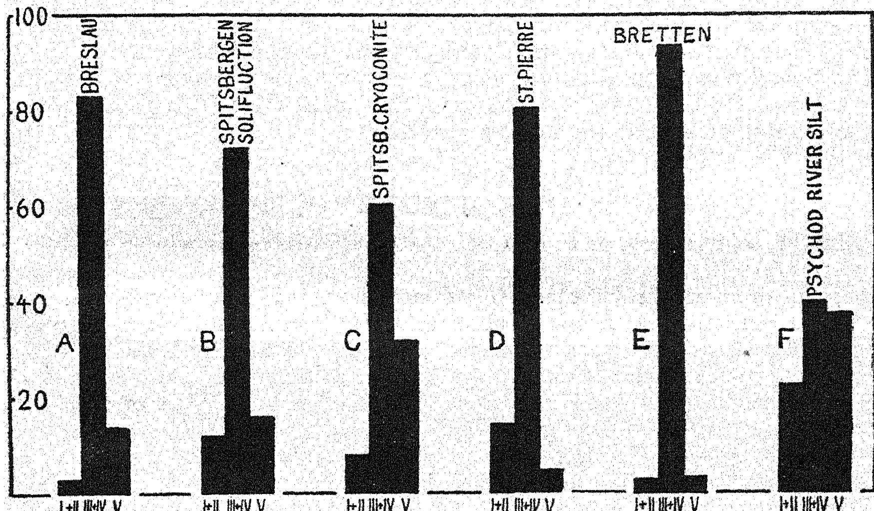


FIG. 3.—Mechanical analysis of various kinds of silts. Grades of coarseness: I + II, 0–0·01 mm.; III + IV, 0·01–0·07 mm.; V, 0·07–2·0 mm.

A. Wind-borne dust collected on snow after a dust storm. From Breslau, Silesia, Germany.

B. Striped solifluction soil. From Spitsbergen. Sample supplied by H. Knothe.

C. Cryoconite, wind-blown dust from the surface of a glacier. From Spitsbergen. Sample supplied by H. Knothe.

D. Younger Loess, from St. Pierre-les-Elbeuf, Seine Inférieure, France.

E. A Mesozoic "loess," of middle Muschelkalk (Triassic) age, from Bretten, Baden, south-west Germany.

F. A river silt, or floodloam. From Psychod, Upper Silesia.

size are produced in arid and semi-arid regions. The cover of vegetation being absent or interrupted, the dust is readily carried off by wind almost as soon as it is formed,* and deposited in the adjacent steppe zones where grass and other low-growing vegetation arrests the load of the wind. It is worth mentioning that Dücker (1937*a*) has arrived independently at the conclusion that the grading of the loess is due to the mechanical disintegration of the

* The coarse material, therefore, remains, and the dust does not accumulate to form pure loess-like deposits on the spot.

rocks in frost climates. He found that the fine earth of a stone-ring in the Riesengebirge, Sudeten Mts., resembles a loess in grading. Another example. a striped solifluction soil from Spitsbergen, may be given here (Fig. 3, B).

The second cause of the uniform grade of coarseness of loess appears to be that the typical loess-grade of 0·1–0·01 mm. is fine enough to be carried even by moderate winds. If this were not so, Recent dusts like that from Breslau (Fig. 3, A), consisting entirely of detritus picked up in a town, could not be accounted for. It is a coincidence that dust of the grade produced by mechanical weathering is eminently suitable for æolian transport, but this coincidence accounts for the wide distribution of loess-like deposits on the earth.

A bed of loess in a section, therefore, can always be interpreted as representing a phase of steppe conditions, and, in temperate Europe, one with a low temperature. More details concerning the loess problem may be gathered from papers on the climate of the countries surrounding the ice-sheet of the Pleistocene (Grahmann, 1932; Zeuner, 1934*a*, 1937), and from another on British loess (in preparation).

D. FROST SOILS AND SOLIFLUCTION PHENOMENA.

In the cold regions of to-day, the seasonal freezing in winter modifies the structure of the soil (Högbom, 1914). This applies particularly to areas where, in summer, the soil thaws to a depth of a few feet only, whilst underneath, a permanently frozen horizon extends sometimes to great depths (over 200 metres have been measured). This permanently frozen sub-soil (Schostakowitsch, 1927; Stoltenberg, 1935) is called *tjæle*. All the phenomena described below depend on frost and snow, and nearly all of them on the existence of tjæle in the ground.

The phenomena in question are very commonly included in the term "solifluction." This is not correct, however, as there are two rather different groups of phenomena, for one of which "solifluction" is a good and descriptive expression, whilst the other has been termed, less adequately, "polygon soils." Both groups may be covered by the term *frost soils*.

SOLIFLUCTION.—In the arctic and alpine zones of to-day and (as evidence has shown) in the periglacial zones of the Pleistocene, frost weathering produces very large quantities of rock debris. This would accumulate on the slopes of mountains and hill-sides, did not *solifluction* remove it rapidly. In spring, the snow cover melts and, since the tjæle prevents the water from draining to deeper levels, the thawing surface layer is soaked with water to such an extent that the debris glides down the slope as a semi-fluid mass. In summer the supply of meltwater ceases and the process comes to a standstill, to be resumed in the following spring. The term "solifluction" was first applied to it by Andersson (1906).

SOLIFLUCTION DEPOSITS.—Solifluction produces huge masses of unstratified or indistinctly stratified debris at the foot of the hills and on the lower portion of the slopes. The occurrence of such deposits in Pleistocene sections has been known for many years in England (Wood, 1882, p. 718; Reid, 1887) and in central Europe (Blanckenhorn, 1895; Lozinski, 1912; Salomon, 1916; Gripp, 1924; Kessler, 1925), and more recently Breuil (1934) has published sketches of sections exhibiting solifluction deposits

(and polygon soils) in France and England. Two English terms are in use for solifluction deposits, but both have somewhat restricted meanings. They are *coombe rock* for those composed chiefly of chalk and similar limestones, and *head* for angular debris of other rocks, often mixed with loess. Other deposits have been called *solifluction gravels*, etc., according to their composition.

SLUDGE.—Though genuine solifluction deposits provide evidence for severe cold during the time of their formation, it is by no means easy to distinguish them from ordinary *sludge*, hill-wash or land-slide, such as occur locally in all climatic zones. Not every unstratified bed of river gravel, for instance, is the result of periglacial solifluction, and in many a case of "solifluction" mentioned in literature one wishes that less ambiguous evidence for a frost or snow climate had been produced.

POLYGON SOILS.—The other group of frost soils does not require slopes for its formation and is restricted chiefly to more or less level ground. These are the *polygon soils* (see, for instance, Elton, 1927; Huxley and Odell, 1924; Huxley, 1925). The name is not very appropriate, since several structures comprised by it are not polygonal. No better term, however, is available at present.*

The common feature of the polygon soils is that in the zone of annual freezing and thawing displacements of material take place, often resulting in structures like rings or network appearing on the surface. A sorting of the soil matter into coarse and fine is often associated with their formation. Although many details of the processes involved are still unknown, they are clearly based on the unequal expansion and contraction of cooling water. It is well known (*a*) that water between + 4° C. and 0° C. expands its volume instead of contracting (water therefore is densest and heaviest at + 4° C.), (*b*) that the volume of ice at 0° C. is by one-eleventh larger than that of water at the same temperature, and (*c*) that ice contracts with increasing cold in the same way as other matter.

These three factors, combined with the unequal capacity for conducting heat of the various rocks and mixtures of soil and water, produce a great variety of curious structures in the freezing soil. It is advisable to consider first the influence of (*b*) on the soil, as it is simpler than that of the others.

MUD POLYGONS.—*Mud polygons* are found on clays or other fine-grained soils in arctic regions. They form fields of polygons separated by cracks or strips of vegetation. The polygons are bulged up in the centre, and show no sorting of material into coarser and finer grades. The diameter of the polygons varies from one to several feet. Elton (1927) has made observations which show that these mud polygons are due to the expansion of the water-logged soil when freezing. Experiments carried out by Dücker (1937*a*, 1937*b*) and others support this view. Wet soils composed chiefly of clay (including boulder clay) or silt (including loess) not only expand considerably when freezing, but layers of clear ice are formed within the soil. The consequence of this expansion is that the surface is bulged up. Many such bulges are formed in a mud area, as observed by Hawkes (1924) in Iceland, and their limits often are polygonal because of the crowding. In summer the mud-bulges dry, and drying-cracks intersect the field. These cracks have nothing to do with the frost cracks described later on.

* In German, *Strukturboden* = structure-soil, is used.

Wet sands expand much less than does mud when freezing, so that polygons of the described type are restricted to surfaces of clay or silt.

Mud polygons have not yet been found in the fossil state. This is not surprising, since no sorting takes place and only minor movements of material occur, and once the frost has gone, little is left that might serve as evidence for a frost soil having existed in the locality.

Trail.—Another type of frost soil is known from geological sections only, because it does not create conspicuous surface features. It is the *trail* observed in stratified, often loamy or clayey, deposits, and consists of contortions and foldings of bedding planes which are frequently drawn out towards the surface. In many cases the original stratification is still discernible. Cases, however, in which a mixture of coarse and fine soil has evidently become separated, have to be referred to the brodel soils (see below). The term *trail* is at present used to cover both types of contortions if observed in geological sections. In fact it is quite likely that the majority of trails are the compound product of expansion trailing and of brodel soil formation.

Expansion Trail.—Pure *expansion trail* is hardly more than a variety of the mud polygons, though formed in a stratified and less viscous soil. The freezing expansion is unequal, and the formation of layers of clear ice alone must result in a disturbance of the original bedding. Moreover, the expansion due to the freezing of the top layer in autumn exerts pressure on the water-logged soil underneath, and when the time comes for the latter to freeze, the expansion can no longer be relieved in an upward direction, and folding of the layers results.

Furthermore, the annual freezing of the soil from above cannot proceed at the same pace everywhere. Differences in wetness, conductibility of heat and the presence of patches of vegetation will cause the frost to proceed downwards irregularly. Freezing expansion, therefore, cannot act uniformly, and unfrozen material must be displaced by the expanding freezing cores. Small though all these movements may be, they are repeated annually with a cumulative effect.

It is evident, therefore, that the bedding planes of a soil resting on tjæle cannot remain undisturbed. The real problem of the trail is that the layers are often drawn *upwards* in places. One explanation for this is offered in the theories suggested for the brodel soils, but it may be that the top layer, freezing and expanding in autumn, breaks up here and there and affords cracks in which the water-logged soil could rise.*

Brodel Soils.—The best-known type of frost soil structures are the *stone-rings* and *stone-polygons*. They appear as rings of from one to several feet diameter, containing fine earth in the centre and stones around the periphery. Cross-sections have revealed the fact that this difference extends to some depth, but does not reach the tjæle. Single structures form rings, and where crowded, they make up a regular polygonal network. If situated on a slope, ovals or stripes result (*stone stripes, striped soil*), owing to a combination with solifluction.

Soils of this type have been described from many arctic countries, especially from Spitsbergen, but they also occur in Antarctica and on moun-

* Such cracks have been observed in Siberia on hills formed by underground ice lenses, called "underground naledj." (See Schostakowitsch, 1927.)

tains (Scandinavia, Sudeten, Black Forest, Alps, Lake District, Scotland, Andes, etc.; see Poser, 1933 for references). Stone rings and stone polygons are more widely distributed than other types of frost soil, and in temperate regions the tjæle may be replaced by an impermeable rock surface, but everywhere a snow-climate is required for their formation.

Stone-rings and -polygons cannot develop on other than mixed soil composed of coarse and fine debris. In the absence of a better expression, Gripp's *Brodelboden* (boiling-up soil) may be used as a descriptive, though not necessarily explanatory, term covering all the varieties of stone-rings and stone-polygons. As regards their mode of formation, two different theories have been proposed, Högbom's theory of regelation (1914), and Low's of convection currents (1925).

Regelation Theory.—Högbom (1914) and others, most recently Poser (1933), hold the view that repeated freezing moves the stones contained in the mixed soil upwards to the surface, leaving the finer earth behind. This transport is a known phenomenon and is called frost-heaving; it is effected by thin layers of ice which form under and around the stones and lift them, and which are replaced by mud in spring, the stones thus being prevented from regaining their former position. The fine earth bulges up in the manner of the mud-polygons, and stones which have reached the surface of the bulge are supposed to be shifted radially outwards down the very gentle slope of the bulge, by repeated freezing and thawing. At the periphery of the bulge they accumulate and form the stone-ring.

Convection-current Theory.—A very different explanation has been put forward by Low (1925). It relies on the fact that water is heaviest at + 4° C. This theory has been vigorously taken up by Gripp (1927, 1929). Dücker (1933, 1937*a*, *b*) considers that the regelation theory is not sufficient, and that convection-currents as postulated by Low and Gripp are possible under certain conditions. In short, the theory is as follows:

In spring and early summer, when the soil above the tjæle is intensely water-logged, periods occur when the temperature at the surface is about + 4° C. At the contact with the tjæle the temperature is about 0° C. The water from the surface will therefore sink down and that from the lower layers rise. Convection currents are thus initiated which are supposed to carry the stones to the surface and outwards to the ring, where they are deposited.

Evidently the question is whether the water-logged soil is diluted enough for the difference in density of the water to become effective in moving soil and stones, or whether the suspension of soil in water has to be so diluted that stones would sink to the bottom by their weight rather than rise with the currents. Experiments and calculations have shown that certain fine-grained soils become movable with a water content of only 22 per cent. (Dücker, 1937*a*, *b*); in other words, convection-currents in the soil are possible.* The question whether they are capable of transporting stones has not yet been investigated. Another question is whether the convection is counterbalanced by the internal friction in the soil. This friction must be considerable in earths of the coarser grades, such as do occur in certain types of stone-rings.

Thus it has to be admitted that frost-heaving as well as convection due

* Gripp and Simon (1934) succeeded in producing them experimentally.

to differences in density can start movements in the water-logged soil, but none of the theories so far suggested is entirely satisfactory. The theory of convection-currents requires tjæle, since otherwise the 0° C. level would not be sufficiently constant. Yet stone-rings do occur outside the region of perennial tjæle, as for instance in the high mountains. Here, the regelation theory is at an advantage, though stone-rings have been found the centres of which were not raised. How the stones can migrate to the periphery in these cases cannot be explained by frost-shifting.

It is possible, if not probable, that several causes are at work, and also that the curious restriction of the process to localized centres is originally due to one of the movements described above in connection with the formation of trail. One thing, however, is certain: all observed polygon soils require a snow-climate with an ample meltwater supply in spring.

ICE-WEDGES.—Another interesting phenomenon of the arctic and periglacial regions is that of *ice-wedges*. They require very low winter temperatures for their formation (below − 10° C.). Ice-wedges were first studied by Leffingwell (1915) in Alaska, and later discovered in Pleistocene sections by Soergel (1932) and others (Zeuner, 1935; Selzer, 1936*). According to Leffingwell's observations, they occur in networks, forming irregular polygons of several metres diameter. The same has been observed with certain fossil localities.

Leffingwell found wedge-shaped cracks filled with solid ice and, at the surface, sometimes over two metres wide, forming a polygonal system in certain parts of the tundra. They open, often with a sound and vibration as if from a distant explosion, in very severe frost, when the completely frozen soil contracts (Fig. 4, A). In the following summer the top soil thaws and water percolates into the crack, where it freezes in the level of the tjæle, exerting pressure on the sides of the crack and thus widening it (Fig. 4, B). In the following winter the crack opens again (Fig. 4, C), and the process of widening by freezing-pressure and cracking is repeated every year, with the result that a thick ice-wedge is formed. In the later stages the growing wedge displaces the adjacent strata (Figs. 4, D, and 5). When local conditions change, or the climate becomes milder, soil from the top will migrate into the space formerly occupied by the ice-wedge. This process has been studied in detail by Soergel (1932).

* Since this chapter was written Paterson (1940) has claimed the presence of fossil ice-wedges in the pit of Traveller's Rest, near Cambridge, and several other instances have been observed in England.

FIG. 4.—Four sketches illustrating the development of an ice-wedge. Black: top zone of soil which thaws in summer and freezes in winter. White: permanently frozen subsoil.

A. First winter. Soil frozen throughout. Intense cold causes contraction, and a crack ("frost crack") opens.

B. Following summer. Meltwater fills the crack and soon freezes in the level of the permanently frozen subsoil. The top-soil is thawed, and mud and vegetation close the opening more or less. Some mud enters the crack.

C. Second winter. Owing to intense cold a crack opens within the ice-wedge. In the following summer this secondary crack is filled as described under B.

D. This process is repeated annually, and the freezing pressure of the ice presses the adjoining strata aside. The ice-wedge has become thick, and the bedding in the permanently frozen subsoil is disturbed.

For continuation, see Fig. 5.

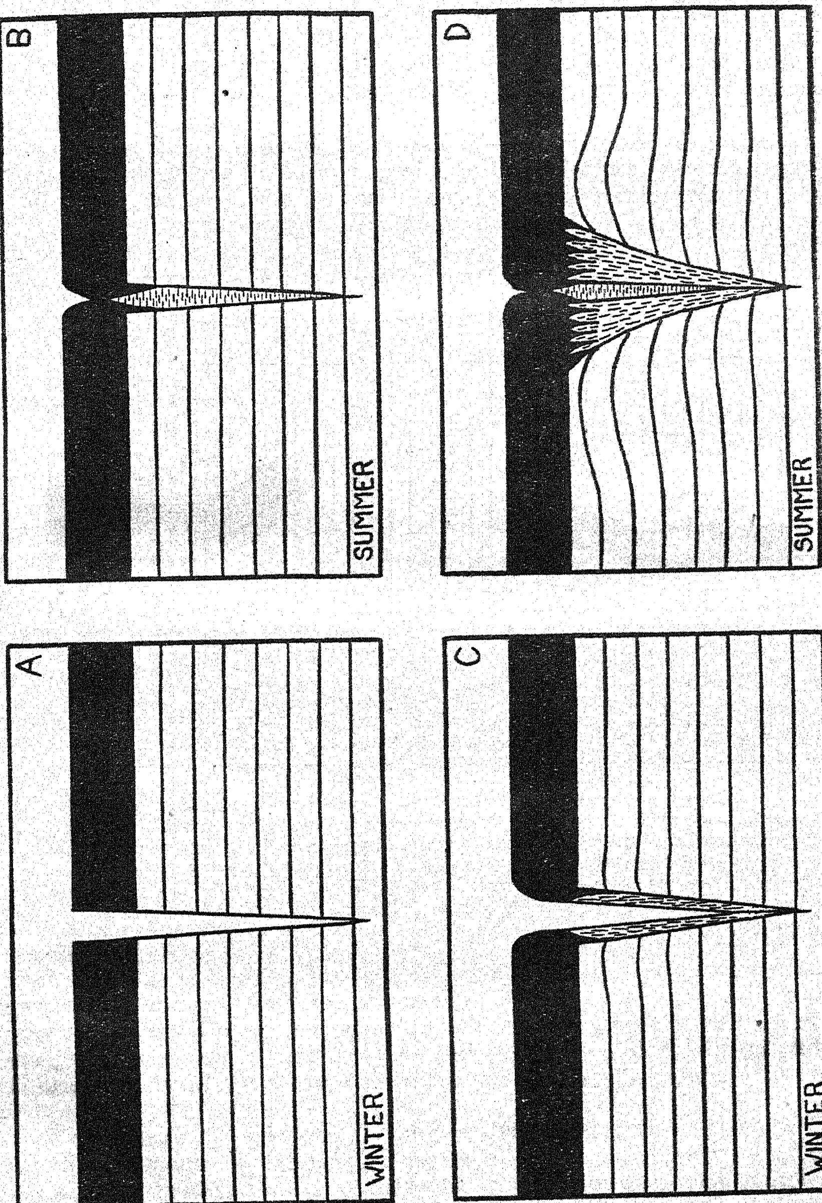


Fig. 4.

Ice-wedges, Recent and fossil, may reach to a depth of 10 m. and are, naturally, confined to the permanently frozen tjæle. In the networks which they form on the surface they are about 10–15 m. apart. In geological sections, the visible shape of the wedge depends to a large extent on the angle between the direction of the crack and the wall of the section (Soergel, 1936).

Summary of Frost Soils.—The study of solifluction and polygon soils has only recently been taken up by a large number of geologists, and many details concerning their mode of formation are still obscure. One point, however, has been firmly established, namely that without exception they require a frost or snow climate for their formation. All varieties occur on permanently frozen sub-soil, and only certain types of stone-rings have been

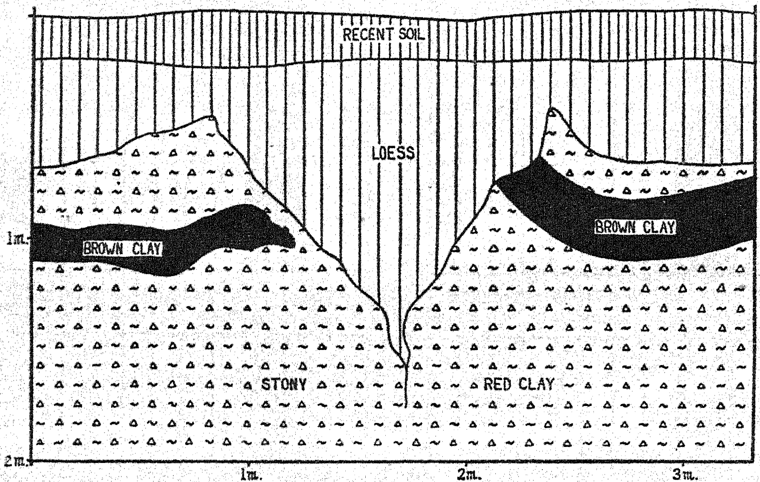


Fig. 5.—A fossil frost-crack, or ice-wedge. Loess covers Permian clay. An ice-wedge occupied and widened a frost-crack cutting through both loess and Permian sediments. When the climate improved and the permanently frozen subsoil disappeared, the ice-wedge melted away, and material from above (in this case, loess) replaced the ice. The lateral distortions caused by freezing pressure are striking. From Mittelsteine, Sudeten Mountains. (Zeuner, 1934*d*.)

found in snow climates where tjæle is absent. For these reasons, the frost soils provide important climatic evidence where they occur in Pleistocene sections. Features suggestive of these phenomena, however, require a very careful scrutiny before they are interpreted climatically, since there are many structures which resemble them but are not caused by the effects of frost.

Temperature Limits for Frost Soils.—The wide distribution of frost soils at the present day enables one to recognize certain climatic limits for their formation. The only variety which is not restricted to areas of perennial tjæle is that of the brodel soils. They are, however, restricted to localities or areas where the warmest month of the year remains below + 10° C. This is the limit for the growth of forests, so that brodel soils are clearly confined to climates which are too cold in summer to allow forests to grow.

This applies to the occurrences in high mountains (Alps, Andes, etc.) as well as oceanic islands (elevated plateaux of Iceland and the Faeroes). From this it would appear that brodel soils require a cool summer for their formation, but it is most probably the absence of high-growing vegetation that really matters. Apart from this, all localities where brodel soils occur have two other features in common: there is plenty of snow in winter, and the temperature hovers about freezing-point for considerable periods during the year. Typical brodel soils, therefore, appear to indicate a snow climate, irrespective of whether the winter is mild or severe. This is the tundra climate of Köppen (1931).

Brodel soils are not restricted to regions with mild winters, so long as the snow cover is sufficient. They are frequent in places where the sub-soil is permanently frozen. Since all the other varieties of frost soils depend on perennial tjæle, the conditions under which tjæle has been observed will provide a further clue to climatic conditions in the periglacial area during the Pleistocene. Perennial tjæle is not confined to treeless regions; in eastern Siberia, for instance, abundant forest grows in a soil of which only about 3 ft. thaw in summer. A necessary condition is that the snow cover is thin and the frost in winter severe, and the annual mean of temperature must be so low that the soil cannot thaw completely. Calculations have shown that the limit is at the annual isotherm of $-2°$ C., provided a snow cover is entirely absent. Otherwise a lower annual mean is required. Tjæle now exists in large parts of Siberia, where the climate is intensely continental and winter temperatures very low, but also in arctic regions, as, for instance, Spitsbergen.

The lowest temperatures are required for the formation of ice-wedges. Continued spells of frost under $-10°$ C. are necessary for the frozen soil to contract and the cracks to open. This figure was obtained by experiments (Hawkes, 1924), but allowing for the cover of tundra vegetation and snow which, though thin, will protect the soil, the winter temperatures in nature must be even lower than this. It is not surprising, therefore, that Recent ice-wedges are known only from a country with a cold and intensely continental climate—northern Alaska.

Geographical Distribution of Fossil Frost Soils.—From the climatological point of view the frost soils may be classified into a group requiring a tundra climate with plenty of snow, but not necessarily with tjæle (brodel soils), a second group which requires tjæle and a fair amount of snow (most varieties except brodel soils and ice-wedges), and a third group which needs a cold, continental climate with intense frost in winter but little snow (ice-wedges).

It is very interesting that the fossil frost soils of the periglacial zone of Europe show distinct climatic differences. *Though none of the varieties is exclusive to any one district*, ice-wedges have been observed more frequently in central and eastern central Europe. Solifluction and brodel soils, on the other hand, though they do occur in the east as well, are much more frequently observed in France and England. The increasing continentality of the climate in an eastward direction is thus demonstrated for the glacial phases, and the more oceanic character of western Europe is evidenced by the relative frequency of frost soils requiring plenty of snow but comparatively little cold in winter.

E. SOILS DUE TO CHEMICAL WEATHERING.

Moraines, loess, solifluction and polygon soils provide evidence of a cold climate. Mild climatic phases are proved by horizons of buried soils due to *chemical* weathering. In all climates with a sufficient amount of precipitation and temperature above freezing-point for at least part of the year, the ground is normally covered with vegetation, and decaying vegetable matter (*humus*) plus rain water draining into the ground exert a powerful disintegrating effect on the material composing it. This process is called *chemical weathering* and the product, *soil*.*

Soils vary enormously in their constitution according to the kind of original rock, the climate of the region, local conditions, such as exposure on slopes and relation to drainage channels. A branch of science, pedology, has developed in recent years, specially devoted to the investigation of soils. A fair amount of knowledge of chemistry is required to understand soil formation.† For this reason, the following explanations are restricted to the possible minimum, and only such types of soil are considered as are found in temperate regions and may occur in Pleistocene sections in a fossilized state.

General Composition of a Soil.—Soil develops on, and from, the exposed surface of some kind of rock, hard or soft, consolidated or not (sands, clays, etc., are rocks in the geological sense), and of varying composition. The composition of the parent rock influences the resulting soil to a great extent, but in regions where the climate favours the development of a certain type of soil, this type will be found on the most diverse kinds of parent rock. This is partly due to the fact that most rocks contain quantities of silica (oxide of silicon, either as quartz or contained in other minerals, such as feldspar, etc.), sesquioxides (oxides of iron and aluminium, the latter an important component of clays), bases, or alkalis (oxides of sodium, potassium, magnesium and calcium, with a basic, or alkaline, reaction), and often calcium carbonate or lime (easily decomposed by acids, leaving oxide of calcium, which is a base). The vegetation supplies decomposing organic matter, called humus, which in certain stages acts as an acid on the soil.

The process of soil formation is studied in a vertical section, often called *profile*. More or less distinct levels characterized by colour and texture are distinguishable; they are called *horizons*.

Tundra Soil.—In cold regions, especially on tjæle, chemical weathering is almost entirely superseded by physical weathering, producing varieties of frost soils. Where there is vegetation it is of the *tundra* type, which consists of *Sphagnum* and other mosses and various other low-growing plants. This vegetation lives under very wet conditions, and this together with low

* In the widest sense of the word, *soil* is the product of the destroying and altering influence of the atmosphere on the surface of the land, under the exclusion of the processes of mechanical transport (denudation and erosion). This definition covers both chemical and physical weathering, and circumscribes the term as used by geologists. In practice, however, "soil," without further qualification, mostly designates a product of *chemical* weathering, and some agriculturists prefer to restrict the term to this group.

† 'Soil, Vegetation and Climate' (Imperial Bureau of Soil Science, 1934); Robinson, 1932; and Wiegner, 1929, may serve as introductions to pedology.

temperature causes the dead plant matter to decompose very slowly. It is accumulated in the form of peat, and its chemical action on the subsoil is very slight.

PODSOL.—Proceeding to somewhat milder regions, one encounters a very striking kind of soil, called *podsol*. It is most typically developed under heath and coniferous forest, though it may occur under other plant associations also. Podsol requires comparatively cool summers with plenty of rainfall. Under these conditions much acid humus containing free humic acids is produced. The humus often forms a blackish band on top of the soil (horizon A_0), and humic acids in solution drain down to the water-table. On their way they attack the minerals constituting the parent rock and dissolve the bases and also the sesquioxides (horizon A_1). Whilst the bases are carried to the water-table, the sesquioxides are kept in solution only so long as the humic acids are not saturated. They are deposited, therefore, at a certain depth, and the horizon formed in this manner is usually intensely brown or red (due to the iron compounds), or black (due to humus or manganese). Sometimes this horizon, which is the *illuvial horizon* of the soil, called B, becomes more or less hardened. Above it leaching takes place, and the soil attains a pale, often whitish colour (A-horizon, *eluvial horizon*). Underneath B the unaltered parent material is called the C-horizon. A podsol is thus characterized by a very distinct separation of the A-, B- and C-horizons. It is evident that a podsol can develop much faster on a parent material which is poor in bases and sesquioxides from the start, so that in regions (such as England) where brown-earths are dominant, podsols are frequently found in areas with sand rich in quartz forming the surface stratum.

BROWN-EARTHS.—It is now easy to understand what happens if the climatic conditions are varied. Let us assume the climate to be warmer in summer than in the typical podsol region, but still with sufficient precipitation. There will be no dry season, but the top-soil will dry up more frequently in summer, be better aerated, with the result that the decaying vegetable matter is more quickly oxidized and much less acid humus produced. Under these conditions, the sesquioxides are no longer transportable, and they remain in the soil. The bases, however, are leached out, including calcium carbonate, and disappear in the ground-water. Whilst the chemical reaction of a podsol is acid for obvious reasons, brown-earths, having lost their bases but containing little or no acid humus, will be neutral or very slightly acid, except in the top layer (A_0), where the decomposition of humus takes place. No distinct A- and B-horizons are developed in a brown-earth which has its brown colour from the oxidized and hydrated iron. An important effect of the washing-out of the bases is that the sesquioxides and colloidal silica are enabled to form plastic colloids of the clay-type. Brown-earths, therefore, are loamy soils. Buried brown-earths are frequently observed in loess-sections, and easily identified by their chemical reaction and their loamy texture, due to the dispersion of the colloids.

Brown-earths are found in temperate Europe in a broad zone from England and France through central Europe into Russia, and they are typically developed under deciduous forest.

CHERNOZEMS.—Let us now assume a climate which is more continental

than that of the brown-earth region, with hotter and drier summers and colder winters, and with a cover of snow. The annual amount of precipitation need not be lower than in the brown-earth region, though it often is. Most of it falls in spring and autumn. Under these conditions steppe develops, the summers being too dry for forests to thrive. The grass grows very rapidly in spring and ripens early, and in summer it dies off, thus supplying abundant organic matter, which is decomposed during the moist seasons, autumn and spring. Downward movement of water in the soil is restricted to these seasons, and what is dissolved in this process is moved upwards again in the dry summer, when evaporation from the surface produces a capillary upward movement of water in the profile. The bases are absorbed by the humus and the clay-colloids which are, therefore, kept in the flocculated state. The soil thus acquires a " nutty " structure, being composed of crumbs. Burrowing animals (rodents, insects, worms) abound in chernozems, and provide for an even distribution of the humus and other components throughout the profile. The burrows of rodents often extend into the fresh sub-soil, where they appear as grey or blackish stripes or patches, the cavities having been filled with black soil from above. They are called *crotovines*.

The term *black-earth* describes this type of steppe-soil very well; but since there are other soils of a black colour, the Russian term *chernozem* (meaning exactly the same) is generally used instead.

The only component which does migrate appreciably in a chernozem is calcium carbonate, since it is dissolved very readily in water containing carbon dioxide. The water which passes down through the decomposing organic matter is naturally rich in carbon dioxide and therefore washes out calcium carbonate. In summer, however, when the movement of the water is reversed, water poor in carbon dioxide rises from the water-table, so that but little calcium carbonate is carried upwards again. It accumulates in the lower part of the profile, often in the form of concretions.

The chemical reaction of a chernozem is never acid because of the presence of the bases in the soil. It rises from neutral to decidedly basic. Chernozem is the soil with the minimum of separation of the A- and B-horizons; it indicates a continental steppe climate with dry and hot summers, It is at present found in south Russia, Siberia, central North America and south-east Australia. During the Boreal phase of the Postglacial and during a phase of the Last Interglacial it extended considerably further westwards in Europe (Figs. 6, 7).

Chestnut Soils and Other Dry-steppe Soils.—A further increase of summer heat and decrease of precipitation lead to a considerable reduction of the cover of vegetation. Steppe may still prevail, but less organic matter and less water are available, and burrowing animals are scarce because of the arid climate. The soils will therefore be thinner than a chernozem and of a lighter colour. They are called the *chestnut-coloured soils*, from their brownish-grey hue. Calcium carbonate is evenly distributed throughout the profile, the chemical reaction of which is alkaline.

Loess Soils.—Dry steppe zones adjoin the deserts with their predominantly physical weathering. Where desert dust is carried by winds into adjacent regions loess will be deposited, the dust being caught by the vegetation in the dry steppe zone. This will lead to a gradual building-up

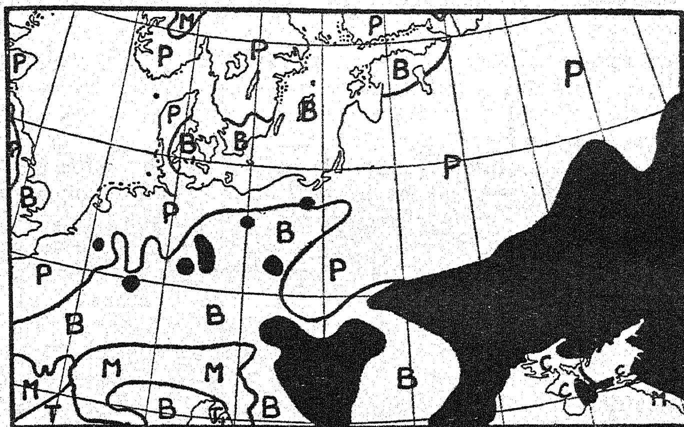


FIG. 6.—Soil chart of Europe, much simplified. Based on 'General Map of the Soils of Europe,' Int. Soc. Soil Sci., 1927. Black: Chernozem. B. Brown-earth. P. Podsol. M. Mountain soils. T. Terra Rossa. C. Chestnut soils. Note the islands of Chernozem in Central Europe, which correspond to relatively warm and dry localities.

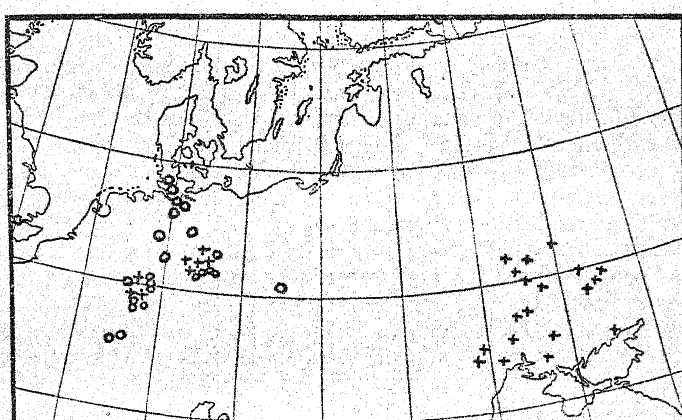


FIG. 7.—Soils of the Last Interglacial. Cross: Chernozem. Circle: brown-earth or podsol. Note the similarity in distribution of the fossil soils with that of the present day (Fig. 6). It indicates that the climate of the Last Interglacial was, for some considerable time, similar to that of the present day. The existence of semi-Mediterranean soils and thick chernozem in certain Last interglacial localities suggests that temporarily the climate was even warmer than to-day.

of the surface with which the vegetation is able to keep pace. Chestnut-soils are, therefore, characteristic of the zone of deposition of desert-dust, or loess.

The loess steppe of the cold phases of the Pleistocene had similar semi-arid conditions, but the temperature was low in summer. The semi-arid character of the soil which prevailed while the loess was being deposited is clearly expressed by colour, texture and distribution of calcium carbonate in the loess. In loess which has not been changed by later weathering, calcium carbonate occurs as a coating of grains, as minute concretions and as incrustations apparently formed around the roots of grass or other plants. This and the yellow or brown colour indicate an affinity of the loess soil to the Recent chestnut soils. The porous structure of the loess is due partly to the rapid addition of dust, and partly to the re-distribution of the calcium carbonate in it, which by slightly cementing the grains helped to preserve the original structure produced by the settling dust and the roots of the plants.

It is essential, therefore, to distinguish sharply (*a*) the conditions of soil-formation prevailing at the time of deposition of the loess, and (*b*) the brown-earth, chernozem or other soils formed on the surface of the loess when the climate had changed and loess deposition ceased.

Mediterranean Red Earths.—So far we have considered the series of soils corresponding to climates of increasing continentality and aridity. It is necessary to consider briefly a second series, branching from the former at the brown-earth type. These are the Mediterranean soils. The main features of the Mediterranean climate are mild and rainy winters combined with hot and dry summers. Chemical activity in the soil, therefore, is concentrated during the wet season, from autumn to spring, and the results are in many respects akin to those observed in a brown-earth climate. In summer the weathering process is interrupted by intense drying up. This appears to influence the degree of hydration of the iron-oxides in the soil. They form compounds poorer in water than are found in brown-earths, and they have consequently a more or less reddish colour. This accounts for the reddish tinge of the Mediterranean soils.

On limestones and other rocks rich in calcium carbonate, a distinct type of red soil develops in the Mediterranean region. Its formation need not be discussed in this context, but its name must be briefly mentioned. It is *Terra Rossa*, the Italian words for red earth. A red earth is merely a soil of red colour, but a Terra Rossa is a soil with very definite chemical and physical characters which develops on limestone in a Mediterranean climate.

Some Points Regarding the Investigation of Fossil Soils.—In order to avoid being deceived by coloured horizons differing in origin from genuine soils, it is necessary to study in some detail formations suspected of being fossil soils before accepting or discarding them as palæoclimatic evidence.

Evidence for Fossil Soils being Genuine.—On discovering in a section a horizon suspect of being a buried soil, the first and most obvious thing to do is to establish whether it *can* have been formed by weathering of the underlying fresh material. If, for instance, the fresh substratum contains large flint pebbles and the layer suspected of being a soil contains

none, its soil-nature is doubtful, since flint is usually little affected by the weathering process in temperate and cold climates.

Most often the weathering soil is loamier than the fresh bed-rock or substratum. If the latter is a solid rock, limestone or granite for instance, this is obvious enough, but it applies to gravels, loess, brickearths and clays as well. Apart from mechanical disintegration, the main reason is that the colloids (which were coagulated by calcium carbonate and other solubles) are set free in consequence of the solubles being leached out. Thus they are able to display their "colloidal" qualities, giving the soil a sticky, "loamy" texture.

Use of Mechanical Analysis.—This dispersion of the colloids, very typical of brown-earth, affords a subtle way of recognizing weathering horizons. The dispersion increases the amount of finest matter, compared with the unweathered parent material, and this is easily revealed by mechanical analysis. As examples, analyses of the loess sections of St. Pierre-les-Elbeuf, on the Seine (p. 81, Fig. 26), and the Ebbsfleet near Gravesend, on the Thames (p. 127, Fig. 41), may be referred to.

Humic Matter in Buried Soils.—Good evidence for a fossil soil is sometimes supplied by the presence of humic matter in the A- and/or B-horizons of the suspected profile. Not everything black, however, is humus, and experience has shown that many a band of oxide of manganese has been claimed as a humic layer representing a soil. The presence of humus, therefore, has to be established by chemical tests.

In well fossilized soils, however, the original contents of humic matter have often disappeared.

Decalcification of Soils.—Where, in a humid climate, the unweathered parent material contains calcium carbonate, the upper portion of the soil formed will be free from it. Fresh loess, for instance, is nearly always more or less limy, and in temperate Europe the soils formed on it are decalcified. Hydrochloric acid provides a simple means of testing sections for the presence of calcium carbonate in the field and thus of finding possible weathering horizons. For a thorough investigation, however, it will often be necessary to determine calcium carbonate by quantitative analysis, and to find out under the microscope in which form it is present.

pH Value, Concentration of Hydrogen-Ions.—An important means of studying the changes due to the leaching of soluble matter under the influence of water, carbon dioxide and humic acids is provided by the determination of the "pH value." This expresses the concentration of hydrogen-ions in the soil. Pure water is "neutral," and the number of hydrogen-ions present in it marks the point of neutrality. An excess of hydrogen-ions characterizes acids, and a deficiency, bases (alkalis). For mathematical reasons the figure used as "pH value" is smallest for the highest concentration of ions, and conversely. Pure water has pH = 7, acid soils yield values below this figure, down to about 3·5 in certain podsols, whilst alkaline soils and certain unweathered rocks have a pH greater than 7, though rarely above 9. The pH-values will be given later for several sections of buried soils.

The study of fossil, or buried, soils is as important as it is neglected. They are of the greatest value as evidence for interglacial and interstadial phases.

F. TRAVERTINES.

Apart from fossil soils which, owing to their general distribution, will always supply most of the evidence of mild and moist phases during the Quaternary, there are certain limestone deposits of local character which have acquired some fame as indicators of climatic conditions. These are the limestone tufas, or travertines, produced by springs rich in calcium carbonate.

The water which issues from such springs contains carbon dioxide, which keeps a large quantity of lime in solution. As the carbon dioxide evaporates or is absorbed by plants, calcium carbonate is deposited, and terraces and walls of varying shape are built up. Vegetation greatly assists this process, since aquatic plants absorb carbon dioxide and thus release lime, and all sorts of vegetable matter serve as nuclei for the precipitation of calcium carbonate, in which they are rapidly enveloped.

In some sections of travertines, such as those of Taubach and Ehringsdorf, near Weimar (Soergel, 1926), Cannstatt, near Stuttgart (Soergel, 1929), and Kharga Oasis (Gardner, 1932, 1935), interruptions of the process of formation of travertine occurred which can be explained only by periods during which the springs ceased to flow. These periods have been interpreted as phases of a dry climate. Everywhere the formation of travertine requires a fairly constant water supply and, therefore, a humid climate.

The flora and fauna enclosed in travertines often are of considerable importance, and help to substantiate conclusions based on purely geological observations.

G. RIVER TERRACES.

An important part in modern Pleistocene stratigraphy is played by river terraces. According to their modes of origin, three kinds of river terraces may be distinguished: (1) tectonic, (2) thalassostatic, and (3) climatic terraces. There is a tendency of local workers to neglect, or even deny, the existence of any other but the type of terraces found in their own district, and many a fruitless controversy has ensued. Furthermore, the fact that certain terraces carry a thick sheet of gravel (aggradation terraces) whilst others do not (erosion terraces) has, though important, often been interpreted in an incorrect manner.

A permanently flowing river would be in a permanent state of erosion, provided there occurred no oscillations of the sea-level, or fluctuations of climate, or tectonic movements of the ground. Such a river would cut down its bed all the time and everywhere, and its thalweg curve would approach roughly a parabolic shape, being steeper near the source.* It would not be able to form terraces.

All terraces, in fact, are due to interruptions or sudden intensifications in the otherwise continuous process of down-cutting.

TECTONIC TERRACES.—One possible source of such disturbances is tectonic subsidence or uplift of part of the river's course (see, for instance, Soergel, 1923). In nature, these movements may be extremely complicated and, since tectonic terraces have little significance for the general chronology of

* This is a greatly simplified statement, though sufficient for the present purpose.

the Pleistocene, only two, much simplified, examples are given here. These will at the same time help to explain the thalassostatic and climatic terraces as well.

UPLIFT OF UPPER COURSE OF RIVER.—Let us assume that the course of the river is crossed by a fault and that the entire upper portion of the river has been raised (Fig. 8). A waterfall, or rapids, will then be formed where the river passes from the raised block down to the stable portion, and increased erosion will gradually gnaw back the upper edge. After some time no more will remain than a portion of the river's course, with a gradient steeper than above and below; it will join smoothly with the lower portion of the thalweg curve, but its upper end will be represented by a distinct break in the curve, which will become weaker and weaker the more it works itself upstream. Such break is called a *knickpoint*. The remnants of the ancient level of the river from the knickpoint as far as the fault will form a "terrace" which, at the fault, runs out into the air. The gravel sheet of such terrace will be thin (*i.e.* about equal to the depth of the river), since no aggradation took place.

In reality the movement at the fault is rarely sudden, and the shape of the resulting thalweg curve depends on the relation between the rates of uplift and erosion. If the rate of uplift is greater, a break of the curve will be observed at the fault. For the present purpose, however, it is not necessary to enter into these details.

SUBSIDENCE OF UPPER COURSE OF RIVER.—The second case to be discussed here is that of a subsidence of the upper course of the river (Fig. 9). In this case the fault will create a bar crossing the thalweg. It is very obvious that this bar prevents much of the pebbles, sand and mud from travelling further down the river, and the break at the fault will, after some time, be filled in with deposits. This "aggradation" (unless it takes place in a lake) will rise slightly upstream, but its gradient will be smaller than that of the portion of the upper course above it. In this portion erosion will continue, until the break at the upper end of the aggradation is smoothed out.

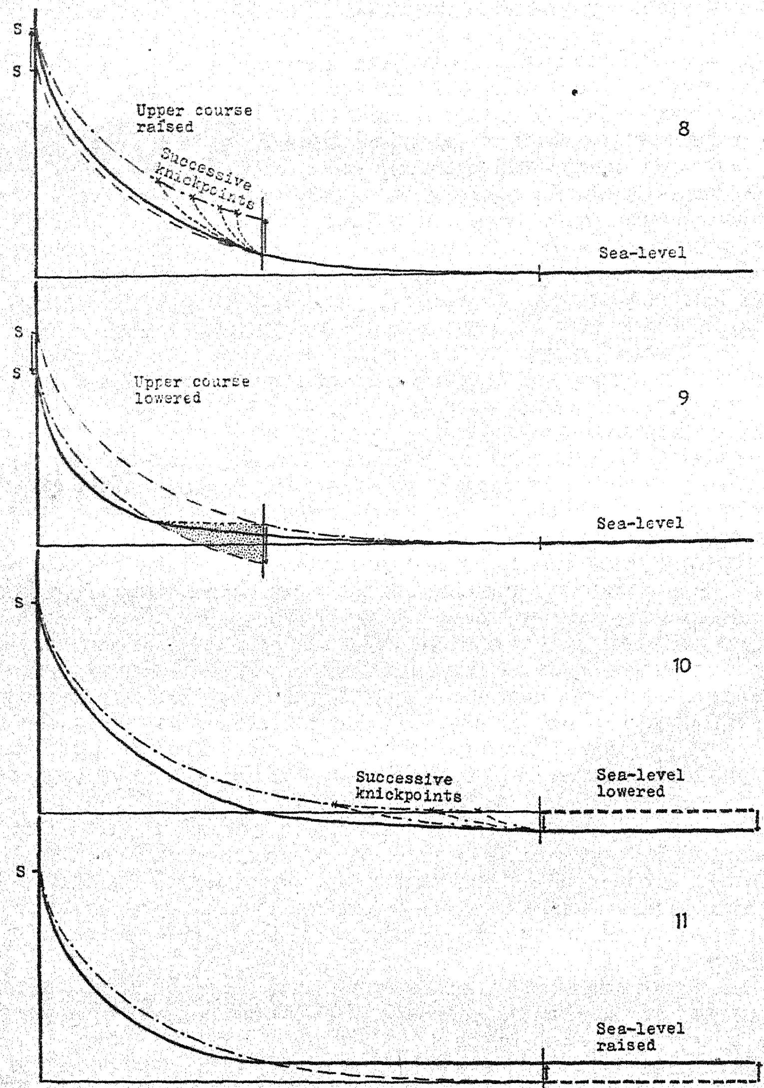
The break at the fault is of the shape of a knickpoint, and the normal erosion of the undisturbed lower course of the river will smooth it out, gnawing a channel across the fault into the aggradation. The result is that a terrace remains at the side of the valley, which is not parallel to the modern thalweg and which, in its middle portion above the fault, consists of aggraded river gravels.

It is important to note that the result of tectonic displacement on the courses of rivers is generally continued or intensified erosion, whilst aggradation is confined to local stretches.

THALASSOSTATIC TERRACES.—It is now easy to understand the second type of river terraces, i.e. those caused by fluctuations of the level of the sea. They are conveniently termed *thalassostatic terraces*.

A drop of the sea-level creates a step at the former mouth of the river (Fig. 10), which is gradually moved upstream by erosion. The result is a knickpoint and a terrace which diverges from the later thalweg in the downstream direction and ends abruptly at the coast. This case corresponds to that of a tectonic rise of the upper course of the river.

A rise in sea-level (Fig. 11) usually leads to the formation of a funnel-



FIGS. 8–11.—Thalweg curves of rivers under the influence of disturbances. Broken line: original thalweg. Dash and one dot: terraces. Two dashes and one dot: intermediate stages. One dash and two dots: aggradation terraces. Full line: new thalweg. For details see p. 20.

Fig. 8—Upper course raised at a fault.

Fig. 9.—Upper course lowered at a fault.

Fig. 10.—Sea-level lowered.

Fig. 11.—Sea-level raised.

shaped estuary (or a fjord). If this is shallow enough and the river carries a sufficien amount of detritus, the estuary will be filled up gradually. There may also be some aggradation above the new high-water mark, if and as the river pushes out an estuarine delta seawards, and this aggradation will work slowly upstream ; but in the upper course of the river, to which the aggradation does not extend, down-cutting continues, as in the case of the upper course of a river under the influence of tectonic subsidence.

Examples of thalassostatic terraces will be found in the chapters discussing the Somme and the Thames (Chapters III and IV), and the fluctuations of the sea-level (Chapter IX). Here it suffices to say that, unlike tectonic terraces, thalassostatic terraces are of great stratigraphical value where it can be established that they depend on *eustatic* fluctuations of the sea-level (see pp. 92, 116, and Chapter IX).

CLIMATIC TERRACES.—The last kind of river terraces to be discussed are those of climatic origin. They are the most important from the stratigraphical point of view as they, of all kinds of terraces, provide direct evidence of climatic fluctuations suitable for a relative chronology to be based on.

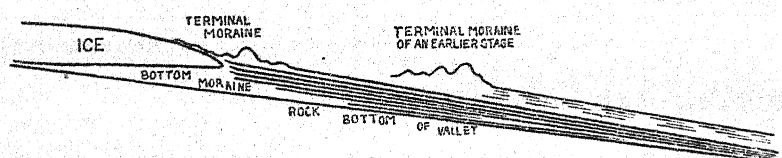


FIG. 12.—Morainic aggradation terraces, formed by the meltwater of an ice-lobe. The aggradation is usually thickest near the source, i.e. the end of the glacier. It decreases in thickness downstream ; its surface, therefore, converges with the rock-base downstream. Similarly, earlier and later phases form a convergent system of terraces.

MORAINIC OR GLACIFLUVIAL TERRACES.—Terraces connected with the moraines of glaciers, as they occur in the zone surrounding the margins of Pleistocene ice-sheets, may reveal a succession of climatic events, though they depend much on purely local conditions. Streams of meltwater which formed near the edge of the ice (frequently building up gravel plains sloping away from the ice, so-called *sanders*) united to form rivers full of load derived from the moraines (Fig. 12). As they flowed into an area with a cold and comparatively dry, periglacial climate, irregular and often insufficient water supply made them drop much of their load, thus causing the aggradation of gravels. Subsequently, down-cutting transformed the gravel sheets into terraces. Terraces of this kind are often made up of very thick aggradations, which, however, do not extend far downstream.

Glacifluvial* aggradation terraces have been used in the Alps by Penck and Brückner (1909) for the fundamental divisions of the Alpine Ice-age, and more recently Eberl (1932) has made use of them in a remarkable attempt to reconstruct a very detailed chronology, and Troll (1926) determined with their aid the stages of the retreat of the Last Glaciation in Bavaria. In the area of the Scandinavian glaciation they are of no signifi-

* *Glacifluvial* is more correct than the more common term, *fluvioglacial*.

cance except for the substages in the retreat of the last ice-sheet (see, for instance, Zeuner and Schulz, 1931).

OTHER TERRACES DUE TO OSCILLATIONS OF WATER SUPPLY.—All other climatic terraces are due to fluctuations between dry and wet. A river in a region with a humid climate flows through a country covered with vegetation. Consequently, little rock-waste is delivered to the river, which has

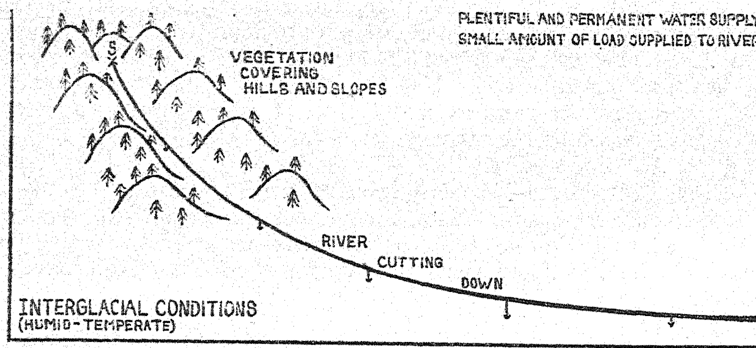


FIG. 13.—A river cutting its valley under ordinary, humid-temperate, conditions.

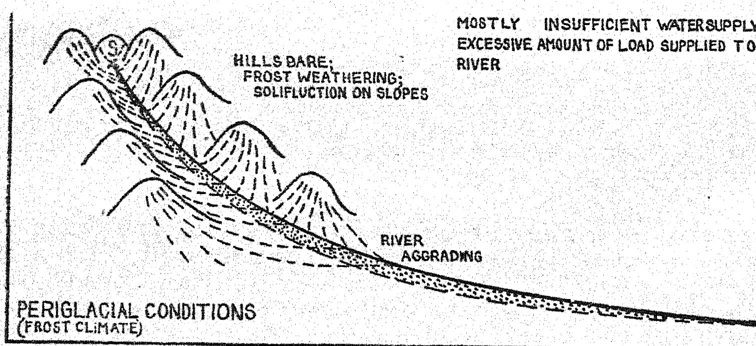


FIG. 14.—A river aggrading a gravel-sheet under the influence of the periglacial climate.

ample water to carry its load. Rivers of this kind continue to erode their beds by down-cutting (Fig. 13).

A river in a region with a dry, arid or semi-arid climate flows through a country which is mostly barren, the rocks being exposed to physical weathering (Fig. 14). Plenty of rock-waste, often of a coarse grade, is delivered to the rivers which suffer from an irregular and often insufficient water supply. The load is carried chiefly in periods of floods and thrown down when these subside. Such rivers build up their beds by adding sheet after sheet of gravels, and thick aggradation deposits are sometimes formed in this manner.

If, in any region, the climate is not constant but, say, humid for some

time, then arid for some time, then humid again, *aggradation terraces* will be formed, since the rivers cut down to a certain level in the first humid phase and build up an aggradation in the following dry phase. This aggradation is quickly cut through in the following humid phase and the river continues to erode the bed-rock below its previous level. If another dry phase intervenes, the corresponding aggradation will be built up from a level lower than the first and so forth.

Successions of climatic terraces are found in many countries. *Where local conditions, or tectonic movements or changes of the sea-level, have interfered with their development, it is often difficult, if not impossible, to reconstruct the succession of climatic events. In some districts, however, they are exceptionally clearly developed, and such districts are of primary importance for the chronology of the Pleistocene.* In all cases a careful study of the system of terraces in question is needed in order to establish their climatic origin, or otherwise. The fauna often helps to do this, and also the composition of the gravels, which can be studied analytically (Zeuner, 1932).

Regional Distribution of Climatic Terraces.—Terraces of this kind occur in several of the climatic zones of the present day and of the past. They are observed, for instance, where the climate is now hot and dry but had repeatedly changed to hot and damp in the past. Certain parts of the Sahara and the Sudan provide examples.

They are found also in temperate arid and semiarid regions, such as central Asia, where the climate changed repeatedly from temperate and dry to temperate and humid.

Climatic Terraces in the Periglacial Zone.—Most interesting of all, however, is the present humid temperate region, particularly of Europe, because it can be shown that here oscillations occurred between humid-temperate and dry-cold. These were caused by the cooling effect of the great glaciations (Soergel, 1921). The zone which was under the influence of the cooling effects of the ice is called the *periglacial zone*, or *periglacial area*.

Most of the rivers of this zone had their sources in the moderately high mountains between the Alps and Scandinavia, many of which had ice-caps of an inconsiderable size, or none at all. In the warmer and damper interglacial phases between two glacial phases, the climate was much like that of the present time. The rivers were cutting, and the country, not yet affected by man, was covered with dense vegetation, making superficial removal of weathered materials by denudation nearly impossible. Chemical weathering prevailed, and the rivers received mainly fine-grained detritus. As precipitation exceeded evaporation the streams and rivers were constantly flowing, carrying considerable volumes of water, and strongly eroding.

When the climate became colder, however, the influence of weathering by frost action increased in the higher parts of the mountains. The forests retreated from the higher parts of the ridges, and the more effective mechanical processes of weathering now prepared larger quantities of coarse and fine rock waste which slowly moved down into the valleys. The more severe the conditions became the more solifluction increased, carrying large amounts of waste into the rivers. But the springs of these rivers, being frozen for a great part of the year, supplied less water than before. Only in springtime, when the snow was melting, much water was available ; floods were usual

at this time of the year, and much rock-waste was taken up and carried downstream by the heavily-laden rivers.

Meanwhile the ice-sheet of Scandinavia extended, and a barometrical anticyclone developed above it. This caused the climatic conditions to become colder and drier at the same time; the forest even in the lowlands disappeared more or less completely (this according to the intensity of the glacial phase); and steppes and semi-deserts spread over the country. The rivers, suffering from an insufficient water supply, accumulated their loads mainly in their middle courses, the transporting powers of the water being inadequate as compared with the enormous quantities of waste prepared by frost-weathering.

The open steppes and semi-deserts, as well as the vast plains of newly accumulated river-gravels, favoured the action of wind. No wonder that the higher horizons of gravel terraces contain wind-blown sand and dust and that, when the activity of flowing water was much reduced during the maxima of the greater glaciations, wind-blown material was deposited on the surfaces of the terraces and on the slopes of the hills. This is the loess. It is very important to note that a loess belonging to the same cold phase as the underlying river gravel rests conformably on it and develops gradually from the floodloams. An unconformity between fluviatile deposits and loess indicates that the loess belongs to a later phase than do the river gravels. This feature has been used extensively in establishing the relationship of loesses to gravel terraces in Germany.

When, after the climax of the glacial phase, warmer and more humid conditions returned, the quantity of water carried by the rivers increased once more, and denser vegetation spread over the country, gradually hindering superficial denudation. The rivers resumed their work of cutting, and formed the actual terrace out of the accumulated beds of gravels.

This summary may sound rather deductive but, in fact, it is the abstract of the results of a very large number of investigations which have shown that—

(1) The accumulation of river gravels began when, towards the end of an interglacial phase, conditions became colder.

(2) The accumulation gradually ceased as the following glacial phase passed its climax. This is the time when the loess was deposited.

(3) The rivers resumed their work of erosion as soon as the climate became milder again, *i.e.* still under cool conditions.

(4) The results of investigations into the fauna (distribution of temperate and cool mammals over the horizons within the gravel beds) and of petrological studies (analysis of the gravels) are in full agreement.

A sequence of climatic river terraces, therefore, gives the number of *cold phases* that occurred in the course of time covered by it, which in many cases means the duration of the Pleistocene. It does not give the number of *glaciations* that extended to the neighbourhood of the area under investigation, since not every cool phase need have been intense enough to cause a large inland glaciation.

Terraces: Summary.—It is evident that climatic river terraces provide valuable evidence for the detailed chronology of the Pleistocene. But it is equally evident that the climatic origin of a system of terraces has to be established first. It must be borne in mind that typical climatic

terraces are restricted to districts removed from the influence of the changing sea-level, removed from the meltwater of the glaciers (though this is less essential), and situated in tectonically quiet, or fairly quiet, regions. Furthermore, the rivers must have been subjected to the influence of the periglacial climate. The most-favoured zone in all these respects is in the mountains and hills of west, central and south-east Germany, where, since it formed a wedge between the alpine and Scandinavian ice-sheets, even minor climatic changes left their traces. This is also the area where, for meteorological and geographical reasons, the influences of the continental and oceanic types of climate meet and often interfere with one another.

Thus, the periglacial zone of central Europe has become the birth-place of the detailed chronology of the Pleistocene.

H. EVIDENCE SUPPLIED BY FAUNA AND FLORA.

The fauna and flora enclosed in certain Pleistocene deposits have always played an important part in the discussion of the climates of this period. They serve as evidence (or are supposed to do so) in two different respects, namely (*a*) in a strictly stratigraphical sense, indicating by the presence or absence of certain now extinct species the relative age of the deposits within the stratigraphical scale, and (*b*) in the ecological sense, indicating the environment in which they lived and, therefore, the climate.

STRATIGRAPHICAL VALUE OF FAUNA AND FLORA.—The stratigraphical value of the Pleistocene fauna and flora is restricted. Too many of the modern species were in existence at the beginning of the Pleistocene, though a few became extinct and a few others appeared in the course of this period. As an illustration of the first possibility, the sabre-tooth tiger (*Machairodus*), the southern elephant (*Elephas meridionalis*), and the Etruscan rhinoceros (*Dicerorhinus etruscus*) may be mentioned. They died out in Europe after the Antepenultimate Interglacial or, more accurately, did not survive the Antepenultimate Glaciation. The mammoth (*Elephas primigenius*), on the other hand, is an example of a species which, *in its typical form*, was restricted to the upper Pleistocene (Penultimate and Last Glaciations; for details, see Chapter X).

Sometimes the frequency of occurrence of one or several species provides stratigraphical guidance. The marine shell fauna of the East Anglian Crags has been analysed successfully from this point of view (see p. 105). On land, certain mammals, such as the reindeer, were definitely rare in the early Pleistocene, but abundant in the later stages. One is able, therefore, to obtain some idea of the approximate age of a fauna and its containing deposit from the association and relative frequency of certain species. For a detailed chronology, however, the evidence supplied in this way is rarely sufficient.

FAUNAL EVIDENCE FOR ENVIRONMENT AND CLIMATE.—More important is the environmental evidence afforded by the fauna, particularly with respect to the distinction of glacial, interstadial and interglacial phases. A study of the Pleistocene rhinoceroses, for instance, has revealed that the woolly rhinoceros (*Tichorhinus antiquitatis*) was adapted to life in the steppe and tundra, whilst two other rhinoceroses (*Dicerorhinus etruscus* and *Dicerorhinus merckii*) were adapted to open woodlands (Zeuner, 1934*b*, 1936). The

structure of the body of the mammoth, especially its teeth, reveals that it was an animal of the steppe and tundra, whilst *Elephas antiquus* preferred woodlands and semi-open country. Correspondingly, the later interstadial and interglacial phases are characterized by *E. antiquus* and *D. merckii*, whilst, in the intervening cold phases, the mammoth and the woolly rhinoceros occur. With their accompanying faunas, they alternate repeatedly in the middle and upper Pleistocene.

Space is not available to enter into greater details, but the importance of this environmental evidence is obvious. It often helps to recognize the climate on which the environment depends. Caution is advised, however, and a fair amount of knowledge of the biological requirements of the species is necessary for sound conclusions to be drawn. The concluding chapter of this book is entirely devoted to the succession of Quaternary faunas, and the reader is referred to it for details.

Marine faunas lend themselves to a similar method of interpretation, though to a small degree only, and it is the temperature of the sea alone that may be suggested by the composition of, for instance, shell faunas. The method has met with some success in the Crags of East Anglia (p. 105), in the coastal terraces of the Mediterranean (p. 184), and in the deposits of the Eem Sea of northern Europe during the Last Interglacial (p. 238).

I. SUMMARY.

The preceding review of the climatic evidence on which the stratigraphy of the Pleistocene relies is inevitably short and incomplete. The discussions of the various items are not intended to be exhaustive, but an effort has been made to refer to papers containing references to other publications on the subject.

In the early days of Pleistocene stratigraphy, moraines and glacifluvial terraces received most attention. Unfortunately, an advance of the ice destroys much of the deposits laid down during an earlier advance, and if the second is larger than the first, the latter may escape notice entirely. For this reason systems of subdivisions based on moraines only are unlikely to be complete. The early stratigraphical systems, both of the Scandinavian and Alpine areas, were based on moraines.

In recent years the deposits of the periglacial zone have received increasing attention. Here, the climatic influence of the glacial phases produced deposits like river gravels and loesses, which had a better chance to survive in suitable localities than had the moraines. Moreover, during the intervening temperate phases, chemical weathering produced on these deposits soils which supply valuable evidence for the kind of climate of that time.* River gravels and loesses of the periglacial zone in conjunction with buried soils have provided a far more detailed record of the climatic oscillations of the Pleistocene than moraines and associated deposits.

In addition the study of frost soils (solifluction, polygon soils, ice-wedges), which are restricted to snow- and frost-climates at the present day and occur

* Soils, of course, developed on moraines also, but they are rarely encountered in sections, as they were mostly destroyed by the following advance of the ice. There are, however, several sections in which boulder-clays appear, separated by well-developed soil-profiles.

frequently in geological sections in the periglacial zone, has helped considerably to elucidate the climatic conditions prevailing during the glacial phases.

Finally, fauna and flora, in the morainic areas restricted to a very few interglacial deposits, but much more frequent in deposits of glacial as well as of temperate phases in the periglacial zone, sometimes provide clues to the climatic conditions prevailing at the time, though they are of little immediate stratigraphical value.

Thus, it is on moraines, gravel terraces, loesses, frost soils and chemical weathering soils, and on fauna and flora, that the relative chronology of the Pleistocene is based. The diversity of the evidence affords chances for checking the results, and one can safely say that the agreement of the stratigraphical schemes based on moraines, loesses and terraces respectively has become fairly satisfactory generally. It will be the subject of the following three chapters to supply regional and local evidence confirming this claim, and to derive from it the sequence of the climatic phases which occurred in temperate Europe during the Pleistocene.

CHAPTER II

CLIMATIC FLUCTUATIONS AND RELATIVE CHRONOLOGY OF THE PLEISTOCENE IN THE FORMERLY GLACIATED AREAS OF CONTINENTAL EUROPE AND NORTH AMERICA

A. INTRODUCTION.

In the study of stratigraphy (as in any other science) it has been the natural course that, as research progressed, an increasing number of details have become known. Consequently, many new stratigraphical subdivisions have had to be introduced, and their number is still increasing. This applies to all formations without exception, including the Pleistocene. It is strange, however, that, whilst in other formations detailed divisions are more or less readily accepted, the same thing in the Pleistocene is by some regarded with suspicion.

When Penck and Brückner introduced their fourfold division of the Ice-age, there was at first much opposition to it. Now, more than 30 years later, it is accepted almost universally, but in the meantime research has revealed a number of minor phases within the established scheme, which play an increasingly important part in the relative chronology of the Pleistocene.

The following table is intended to summarize this development of Pleistocene stratigraphy. It also may serve as a chronological guide for the survey of evidence which is to follow.*

Morainic and Associated Deposits as Stratigraphical Evidence.—The main divisions of the Pleistocene of temperate Europe are based on moraines and glacifluvial deposits. It was recognized at an early time that the ice advanced more than once and that, in the intervals, the climate was temperate. These phases have been called *interglacials* or, if of a minor character, *interstadials*.

The most popular stratigraphical scheme is that introduced by Penck and Brückner for the Alps, but the Scandinavian area of glaciation, with its periphery extending from the Ural Mountains through central Germany to Britain, was of much greater importance, especially as regards its climatic influence on the adjacent unglaciated countries. It is advisable, therefore, to discuss the Scandinavian area first.

* Only the barest summary can be given here. Those requiring details will find references in summaries published by the writer (1935, 1937, 1938). Text-books: Woldstedt (1929), W. B. Wright (1937), both however not treating of the detailed chronology.

<table>
<tr><th>Mono-glacialism.</th><th>Biglacialism.</th><th>Penck and Brückner.</th><th colspan="2">Detailed relative chronology.</th><th>Abbre-viations.</th></tr>
<tr><td rowspan="19">Ice-Age</td><td rowspan="11">Second glaciation</td><td rowspan="5">Fourth Alpine glaciation "Würm"</td><td rowspan="5">Last Glaciation</td><td>3rd glacial phase</td><td>LGl_3</td></tr>
<tr><td>Interstadial oscillation</td><td>$LGl_{2/3}$</td></tr>
<tr><td>2nd glacial phase</td><td>LGl_2</td></tr>
<tr><td>Interstadial oscillation</td><td>$LGl_{1/2}$</td></tr>
<tr><td>1st glacial phase</td><td>LGl_1</td></tr>
<tr><td rowspan="3">Third Interglacial</td><td rowspan="3">Last Inter-glacial</td><td>Second part of interglacial</td><td rowspan="3">LIgl</td></tr>
<tr><td>Minor cool phase</td></tr>
<tr><td>First part of interglacial</td></tr>
<tr><td rowspan="3">Third Alpine glaciation "Riss"</td><td rowspan="3">Penulti-mate Glaciation</td><td>2nd glacial phase</td><td>PGl_2</td></tr>
<tr><td>Interstadial oscillation</td><td>$PGl_{1/2}$</td></tr>
<tr><td>1st glacial phase</td><td>PGl_1</td></tr>
<tr><td>Only interglacial</td><td>Great Interglacial</td><td colspan="2">Great or Penultimate Inter-glacial with one or several cooler phases</td><td>PIgl</td></tr>
<tr><td rowspan="7">First glaciation</td><td rowspan="3">Second Alpine glaciation "Mindel"</td><td rowspan="3">Ante-penulti-mate Glaciation</td><td>2nd glacial phase</td><td>$ApGl_2$</td></tr>
<tr><td>Interstadial oscillation</td><td>$ApGl_{1/2}$</td></tr>
<tr><td>1st glacial phase</td><td>$ApGl_1$</td></tr>
<tr><td>First Interglacial</td><td colspan="2">Ante-penultimate Inter-glacial</td><td>ApIgl</td></tr>
<tr><td rowspan="3">First Alpine glaciation "Günz"</td><td rowspan="3">Early Glaciation</td><td>2nd glacial phase</td><td>EGl_2</td></tr>
<tr><td>Interstadial oscillation</td><td>$EGl_{1/2}$</td></tr>
<tr><td>1st glacial phase</td><td>EGl_1</td></tr>
<tr><td>Pliocene</td><td>Pliocene</td><td>Pliocene</td><td colspan="2">Villafranchian (Pliocene)</td><td></td></tr>
</table>

B. SCANDINAVIAN AREA OF GLACIATION.

The Scandinavian area of glaciation* was by far the largest in Europe. Its southern limits, marked by the occurrence of boulder clays, are to the south of Ireland, England from the Bristol Channel to the Thames, Holland at the mouths of the Rhine, the Hartz Mountains, the Sudeten Mountains, Kiev, Pavlovsk on the Don, and the sources of the Dwina. It is doubtful, however, whether these extreme limits were reached all at one time.

Within this vast area it has been found that the zone on the extreme

* See Woldstedt (1929), Madsen (1928), Wahnschaffe and Schucht (1921).

periphery is occupied by deeply weathered moraines which no longer exhibit topographical features due to the action of ice. In many parts they have been removed entirely by denudation and erosion. This shows that they are much older than the inner zones of moraines. It has further been found that two glaciations have contributed to these outermost deposits. The floodloams of two different river terraces in central and east Germany pass into laminated clays which are covered conformably by boulder clay. The earlier of these glaciations has been called *Elster*, and the later, *Saale*.

As one moves towards the central area of the Scandinavian glaciations, one passes more or less distinct lines at which the topographical features, such as terminal moraines, sanders, eskers, lakes and undrained depressions, etc., are in an increasingly better state of preservation, and where the intensity of weathering and denudation decreases. These lines, commonly called " end-moraines " for short, have always been correctly interpreted as stages of the extension or recession of the ice. The most notable of these are (1) the *Fläming* or *Warthe* belt, (2) the *Brandenburg* or *Weichsel* belt, (3) the *Posen* or *Frankfurt* belt, (4) the *Mecklenburgian*, Great Baltic, or *Pomeranian* belt, and (5) the *Fennoscandian* belt (Fig. 15). Since the state of preservation deteriorates from the centre towards the periphery, it might be, and has been, inferred that these belts represent stages in the retreat of one great glaciation.

Interglacial Deposits.—This cannot have been the case, however, Sections in pits and borings revealed that, far inside the margin of the glaciated area, at least two, and sometimes three, boulder-clays occurred, superimposed and separated by beds with fossils of a temperate climate. Thus, the interglacials were established. It must not be overlooked that such interglacial deposits are confined to the area of deposition, which has always been roughly east and south of the Baltic Sea, while the Scandinavian peninsula was the area of glacial denudation which supplied the material laid down further south, east and west.

Borings near Berlin.—As an instance of three boulder-clays separated by two interglacial horizons, the boring carried out at Rüdersdorf, near Berlin, may be quoted (Wahnschaffe and Schucht, 1921) :

0– 22·5 m. : Upper sand and boulder-clay.
22·5– 27·5 m. : Sand and gravels with *E. primigenius*. " Rixdorf horizon."
27·5– 65·4 m. : Lower boulder-clay and sand.
65·4– 81·0 m. : "*Paludina* horizon."
81·0– 136 m. : Lower sand and laminated clay.
136·0–178·5 m. : Lowermost boulder-clay with a horizon of sand, 20 m. thick.

This sequence shows the two well-known interglacial horizons called *Rixdorf Horizon* (see Dietrich, 1932) and *Paludina Bed* (see Heck, 1930), which are regarded by Woldstedt (1929) as the Weichsel-Saale and Saale-Elster interglacials respectively. The three boulder-clays thus are supposed to represent Weichsel, Saale and Elster. But the basal complex of moraine is divided by 20 metres of sand and possibly corresponds to two separate glaciations. The question whether there are three or four bottom moraines in north Germany has not yet been solved, complete sequences naturally being extremely rare. Gagel (1913) distinguished three glaciations.* Van

* Gagel was the first to use weathering horizons as evidence for interglacials.

Wervecke (1927, 1928, 1931, 1933) is convinced that there are six, two of which preceded Elster. He calls the earliest two the *Alster* and *Elbe Glaciations*.

The problem of the number of north German glacial phases is complicated by the Warthe phase, considered as an unimportant stage by some, and as a separate glaciation, or at least a major phase, by others. Petrological investigation of the boulder-clays will, perhaps, settle these questions in the future. Quantitative treatment of the erratics contained in boulder clays has produced results (*stone-counts*, *Geschiebezählung*, Milthers, 1934; Hesemann, 1931, 1934, 1935; Woldstedt, 1935) which are claimed to be promising.

In the Rüdersdorf section, and in many others of the Berlin district, the only bed that can be dated with reasonable certainty is the upper boulder-clay and sand, since the superficial deposits here are those of the Brandenburgian or Weichsel phase. The earlier moraines have been dated by the primitive method of counting downwards, omitting the Warthe phase. At any rate, this and similar sections supply the *minimum* number of ice-transgressions in this district. It is three.

Problem of Correlation of Terminal Moraines and Boulder Clays.—Woldstedt's interpretation of the Rüdersdorf boring is based on the assumption that Warthe was an unimportant oscillation. If one regards Warthe as a phase separated from Saale and Weichsel by retreats to somewhere north of Berlin, it should be represented by a bottom moraine which, again by the primitive counting-method, would be the second from the top. This would make the Rixdorf horizon Warthe-Weichsel, and the Paludina Bed would become the Saale-Warthe interglacial or interstadial.

Rixdorf Horizon.—If one accepts Woldstedt's interpretation, however, one is at once up against the difficulty that the Rixdorf horizon, supposed to represent the Last Interglacial, contains a mixed fauna of cold and temperate elements, which led Dietrich (1932) to the conclusion that the Rixdorf horizon separates Warthe and Weichsel (as suggested above) and is *not* of the age of the Last Interglacial. The fauna and flora of genuine deposits of the Last Interglacial are thoroughly temperate (compare, for instance, Denmark, p. 34; and the Lower Travertine of Ehringsdorf, p. 67). Rixdorf is too cold and continental to match these, but it agrees fairly well with the fauna of the Upper Travertine of Ehringsdorf, found between the Younger Loesses 1 and 2 and separating the two cold phases which represent the Last Glaciation in the periglacial area. For this reason one might be inclined to regard Warthe and Weichsel as the equivalents of the Younger Loesses 1 and 2.

There is, however, no general agreement on the character of the Warthe phase. Woldstedt was at first inclined to combine Warthe and Weichsel as two phases of the Last Glaciation, a view which is still regarded as sound by many writers, but later he suggested that it should be considered as an after-phase of the Saale Glaciation.

Last Interglacial in Denmark.—Much clearer than in north Germany are the deposits of the Last Interglacial in Denmark (Jessen and Milthers, 1928; Madsen, 1928). Here marine faunas and pollen-analysis have contributed to reconstructing the climatic conditions of the Last Interglacial with remarkable results. They may be tabulated as follows:

Stage.			Character of flora.	Climatic conditions and changes of level.	
			Glacial phase (solifluction)		
V.	(Gap.)			Ice advancing.	Skärumhede Series.
	Subarctic flora.		*Betula nana*-heaths, *Betula pubescens*, sparse aquatic flora.		
IV.	Upper temperate flora.		*Betula pubescens*, *Pinus silvestris*, *Picea excelsa*, *Betula nana*.	Ice-edge retreating. Temperate climate in Jutland.	
			Deciduous forest maximum *Brasenia*, *Dulichium*, *Trapa*.		
III.	Middle Bed. Subarctic flora.		*Betula nana*-heaths, subarctic bogs. Northern, sparse aquatic flora.	Glaciation on Scandinavian peninsula. Subarctic climate in Jutland.	
II.	Lower temperate flora.	Coniferous forest.	*Pinus silvestris*-zone. *Picea excelsa*, *Betula pubescens*, *Populus tremula*.	Swamping of bogs.	
			Picea excelsa-zone. *Dulichium* and *Brasenia* rare.	Climate of continental tendency, gradually cooler. Emergence.	
		Deciduous forest.	*Carpinus*-zone. *Picea excelsa*. Oak mixed forest diminishing.		
			Oak mixed forest zone. *Pinus silvestris* rare. *Brasenia*, *Dulichium*, *Trapa*, *Aldrovanda*, etc. No *Picea*.	Eem-submergence. Atlantic climate. Temperature optimum.	
		Coniferous forest.	*B. pubescens*, *P. silvestris*-zone. — *Ulmus* maximum.	Cool, gradually milder, climate continental.	
			B. pubescens, *P. silvestris*-zone. — Deciduous forest appears.		
			B. pubescens, *P. silvestris*-zone. — *Betula*—*Pinus* pure association.		
I.	Subarctic flora.		*Betula nana*, *Salix phylicifolia*.	Melting period of the preceding glacial phase.	
	Arctic flora.		*Dryas*, *Salix reticulata*, *S. herbacea*.		
			Preceding glacial period.		

From this it is evident that the climate of the Last Interglacial was decidedly mild, even slightly warmer than at present, during the phases II and IV, and that a subarctic phase (III, or *Danish Middle Bed*) intervened between these.

The exact relation of these Danish deposits* to the moraines is of great stratigraphical importance but, unfortunately, not quite clear. They lie close to, but outside, the terminal moraines of the Weichsel phase. Whether they also lie outside those of the Warthe phase is uncertain, since the Fläming moraine cannot be traced with any certainty further north than Hamburg. In Vierke's chart (Fig. 15) it is continued to the island of Sylt off the west coast of Jutland, a view based on stone-counts by Milthers (1934). But this author and Hesemann (1931, 1934, 1935), disagree violently about the method of counting erratics, so that one is disinclined to take their claims as the last word with regard to the westward extension of the Warthe phase in Jutland.

Now, the Herning Series sections are never covered by unmistakable ground-moraine, but are generally capped by a deposit which Jessen and Milthers (1928) regard as the result of solifluction under cold conditions. Since, moreover, some of the Danish sites occur in what are still, topographically, completely enclosed, undrained, shallow basins, it seems probable that no ice-sheet has passed over them since their formation. It follows, therefore, that they must either be younger than the Warthe phase, or lie to the west of the limit of this phase.

Further, the semi-arctic Middle Bed itself reveals no evidence of contemporary solifluction. In view of the close proximity of the sites to the Weichsel end moraine (a few kilometres), it therefore seems clear that the cold phase which the Middle Bed records cannot be equated with the Weichsel phase itself. *A fortiori* it cannot be equated with the Warthe phase which was of even greater severity. The Middle Bed, therefore, must represent an independent cold phase of lesser magnitude than either Warthe or Weichsel. And this minor cold phase must have punctuated a thoroughly temperate interglacial of very considerable duration which certainly preceded the Weichsel phase, was certainly subsequent to the Saale phase and must, therefore, either represent the interval Saale-Warthe, or Warthe-Weichsel.

If one regards the extension of the Warthe moraine to Sylt as established, the second alternative is probably the right one, and the entire interglacial section would be later than Warthe. If, on the other hand, Warthe stopped short, east of the Danish sites, the interglacial is likely to precede Warthe. As will be seen from the table, Fig. 17, the latter alternative is tentatively adopted here.

Thus, the problem of the Warthe phase still remains to be solved, but in spite of this difficulty the Danish Middle Bed series shows that, in addition to Elster, Saale, Warthe and Weichsel, there was a minor cold phase which occurred during the Last Interglacial. Further evidence for it is found in the periglacial area, where it appears to be represented by the fourth glacial terrace of Soergel (p. 57).

MASURIAN INTERSTADIAL AND POMERANIAN PHASE.—In the area of the Weichsel moraines three halts may be distinguished, the maximum advance

* These may be called the *Herning Series*.

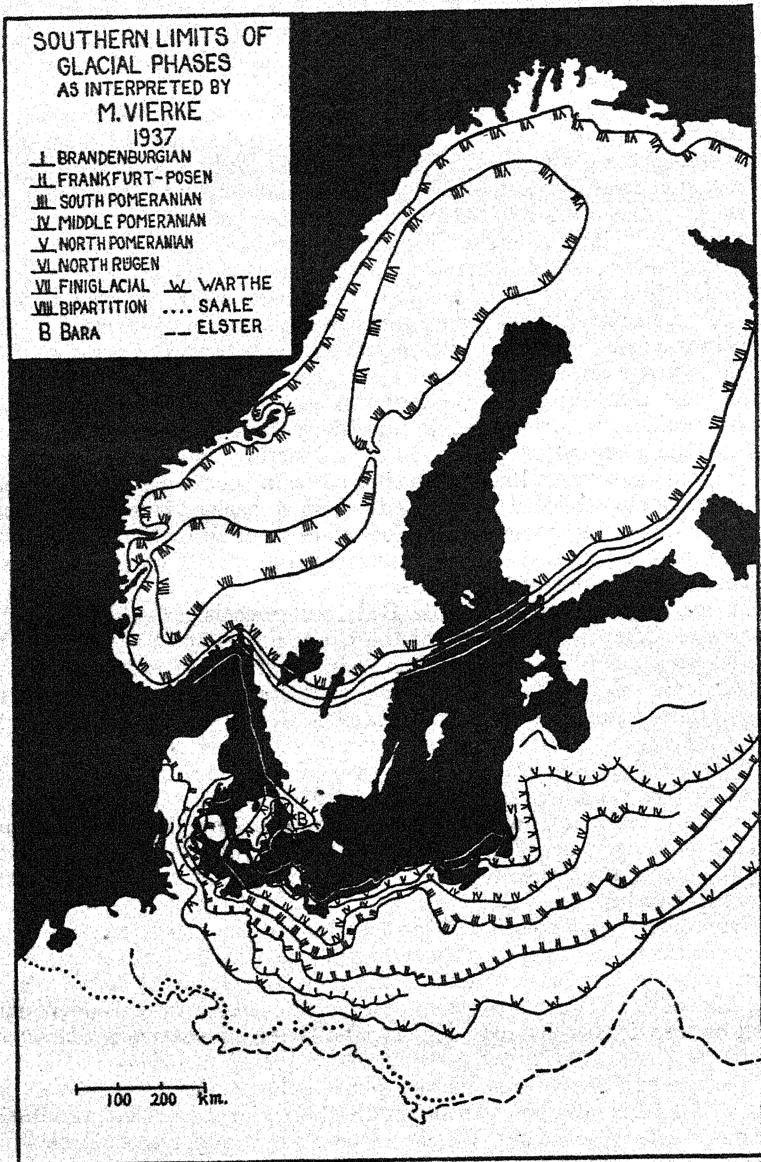


Fig. 15.—Chart of the limits of glacial phases in central and North Europe, as interpreted by Vierke (1937). Note that the Warthe moraine is usually shown as disappearing beneath the Weichsel moraine east of Hamburg.

(Brandenburg moraines), the Frankfurt-Posen belt, and the Pomeranian belt. Where the moraines of the Frankfurt-Posen phase have been examined in detail (Zeuner and Schulz, 1931), they have turned out to be largely due to topographical features ; they need not have been caused by a recrudescence of the climate during the retreat of the Weichsel ice.

The Pomeranian belt, however, is much more individualized. It is distinguished by still greater freshness of its surface features (Galon, 1938), and appears to be the product of a re-advance after a distinct oscillation. This view is supported by the discovery of the *Masurian Interstadial* in East Prussia (Hess v. Wichdorff, 1915). Freshwater deposits containing numerous shells of gastropods and bivalves rest on top of a boulder-clay regarded as that of the Weichsel phase and are covered by a thin bed of more recent boulder-clay. Moreover, they are intensely contorted by the pressure of re-advancing ice. The shell-fauna was studied by Menzel (1915). It is a mixture of decidedly cold forms with others which are climatically indifferent. The flora, studied by Stoller (according to Woldstedt, 1929), included dwarf willow, dwarf birch, and alder ; it corresponds to the present northern limit of tree-growth. The climate, therefore, must have been fairly cold during this oscillation ; nevertheless Woldstedt (1929) points out that there was sufficient time for lakes to be filled in and covered with peat, so that this less cold phase cannot have been very short. The cool climate of the Masurian Interstadial is further evidenced by the fact that buried ice appears to have survived it in the sander zone (Zeuner and Schulz, 1931).

The Pomeranian phase was succeeded by the retreat of the ice to Scandinavia. The Scandinavian stages of the ice-recession will be discussed in Zeuner (1945). De Geer's and Sauramo's varve-countings have shown that these halts were of a short duration (a few hundred years), so that they do not concern us in this context.

North German Phases: Summary.—Thus, the following climatic phases of the Pleistocene have been established within the area of the Scandinavian ice-sheet, chiefly in north Germany, and established without reference to the periglacial and Alpine areas (see table, p. 38).

Relative Extension of Ice-sheets.—In the second column of this table the relative extension of the ice-sheets is given, as the distance of their margins from an assumed ice-centre in north Scandinavia, approximately on a line from the north end of the Baltic Sea through Berlin. The range of the Elster Glaciation has been taken as the unit. Saale and Elster compete locally for the maximum extension. Apart from this, each successive glacial phase was smaller than the preceding. This strongly suggests the possibility of less extended glacial phases being hidden by the major ones, their deposits having been destroyed or covered. The number of glacial phases at present known of the Scandinavian ice-sheet, therefore, is likely to be less than the correct figure.

North Germany: Remaining Problems.—Apart from the problem of the unrecognized minor phases, three outstanding questions remain to be settled in north Germany. The first is whether van Wervecke's Alster and Elbe glaciations can be confirmed. If so, some very early glaciations would be added to the sequence, but this would not affect the positions of the other phases.

	Climatic phase.	Extension of ice-sheet, %.	Morainic and Intermorainic phases.	Climate.
			Postglacial phases. Late Glacial retreat phases.	
Last Glaciation	Third phase.	87·5	Pomeranian Phase.	Glacial.
Last Glaciation	Interstadial.		Masurian Interstadial.	Subarctic.
Last Glaciation	Second phase.	92·5	Weichsel Phase.	Glacial.
Last Glaciation	Interstadial.		Rixdorf Horizon.	Continental, cold to temperate.
Last Glaciation	Position disputed.	95·0	Warthe Phase.	Glacial.
	Last Interglacial, later part.		Skärumhede Series, second part of Last Interglacial.	Mild-temperate ; ? annual mean slightly higher than now.
	Cold oscillation.		Middle Bed.	Subarctic in Jutland.
	Last Interglacial, earlier part.		Eem Series and corresponding deposits, first part of Last Interglacial.	Mild-temperate ; ? annual mean slightly higher than now. Continental at first, oceanic later.
	Penultimate Glaciation.	97·5–102·5	Saale Glaciation.	Glacial.
	Great Interglacial.		Weathering and denudation.	Temperate.
	Antepenultimate Glaciation.	100·0	Elster Glaciation.	Glacial.

The second question is concerned with the Warthe phase. Some workers consider Warthe as post-dating the Last Interglacial, but others are inclined to think that it antedates the latter.

The third question is that of the intensity and position of the Pomeranian phase. All workers except Knauer agree that it is a late stage of the Weichsel glaciation. Some consider the intervening interstadial as a major oscillation, whilst others regard it as unimportant.

An unexpected complication has recently been introduced, however. It affects the position of the Pomeranian in the sequence of glacial phases. Dietrich (1932), interpreting the curve of solar radiation and thus anticipating what should first be proved by evidence in the field, expects the first phase of the Last Glaciation to be smaller than the second. In consequence, he regards Warthe and Weichsel as the second and third phases of the Last Glaciation respectively, and degrades the Pomeranian to a mere halt in the retreat of the Weichsel ice.

From a very different standpoint, Knauer (1935, 1937) suggested that the Pomeranian was really the *first* phase of the Last Glaciation and was *followed* by Warthe and Weichsel. North German geologists have refuted this view (Woldstedt,* Gripp, 1940), which was based on observations in the Alpine area of glaciation (p. 45). It is necessary to emphasize here that, whatever the outcome of the discussion of Knauer's view may be regarding the Alpine phases, in north Germany the Pomeranian has been proved to be later than Warthe and Weichsel.

Polish Moraines.—During the last twenty years much work has been done on the Polish Pleistocene, and it was found that four glaciations, or glacial phases, may be distinguished which, according to Szafer (1928, 1931), are called Jaroslavian, Cracovian, Varsovian I and Varsovian II. Szafer paid particular attention to the mild phases (Sandomirian, Masovian I, Masovian II) separating the glacial phases.

As elsewhere, the number four of the glacial phases induced some workers to correlate them with Penck's Alpine glaciations Günz, Mindel, Riss and Würm (Premik, 1932; Klimaszewski, 1932). But, quite apart from the absence of a certain equivalent of Günz in north Germany and Russia, the belts of terminal moraines, and palæontological evidence also, suggest that the Varsovian I is the eastward extension of the Warthe belt (Gams, 1930; Szafer, 1931), and that the Cracovian corresponds to Saale. The Jaroslavian, therefore, is likely to be of Elster age. The Varsovian II comprises the zone of fresh glacial topography and is rich in lakes. It is identical with the Weichsel phase of Germany.

Russian Moraines.—The divisions of the Russian Quaternary have been discussed by Girmounsky (1931, 1932, 1936) and Mirčink (1936). Girmounsky distinguishes a Neowürm (= Weichsel + Pomeranian of central Europe and Varsovian II of Poland) from a Würm† proper (= Warthe, Varsovian I). Bubnoff (1936) also distinguishes two main phases of the Scandinavian glaciation in Russia. Mirčink (1928, 1930) recognized four stages of the Last Glaciation, of which the second comprises the zone of the lakes and may, therefore, be correlated with the Weichsel phase of north Germany. This is confirmed by Jakowleff (1932), who summarized the

* Appeared 1939 or 1940. Not seen.

† This term is particularly unfortunate in view of its different use in the Alps.

results of mapping work in north and central Russia, and connected the morainic belts of Russia and the adjoining countries with those of north Germany. He found that the moraines of two large lobes in the areas of the rivers Don and Dnjepr—very remarkable features of the Russian zone of old moraines—connect with the Saale moraines of Germany, and that the Warta-Wyčegda belt continues westwards into the moraines of Woldstedt's Fläming- or Warthe phase.

North of these follows the "main belt of terminal moraines" which forms the southern limit of fresh glacial topography and of lakes. It continues into the terminal moraines of the Brandenburgian or Weichsel of Germany. Even the equivalent of the Frankfurt or Posen phase has been identified in Russia. Jakowleff's "inner or north-western belt" is the direct continuation of the moraines of the Pomeranian phase. This was followed by several further stages in the retreat and, finally, by the Finnish Salpausselkä, which are part of the Fennoscandian End-moraine.

This somewhat tedious summary is intended to show that the ice-margins which have been used in Germany to establish the succession of glacial phases are not restricted to that country, but continue around the entire continental edge of the Scandinavian area of glaciation.

Caucasus.—Even in the Caucasus Mountains, the glacial phases appear to agree with those of the Scandinavian and Alpine areas. Mirčink (1928) compared the moraines of the Caucasus with those of north Europe, and Reinhard (1933, 1936) compared them with those of the Alps. Both authors distinguish three or four phases of the Last Glaciation which, according to Mirčink, may be correlated with those of north Europe. Reinhard regards two of these as the main phases. Vardanianz (1933) even proceeds to correlate the individual retreat stages in the Caucasus with those in the Alps.

As elsewhere, so in the Caucasus also, the earlier glaciations afford less evidence for phases, though Reinhard (1933, 1936) is able to distinguish two phases of the Penultimate Glaciation. The Antepenultimate Glaciation appears so far as an undivided glaciation, and traces of what might be considered as the equivalent of the Alpine Günz are very scarce.

Thus, it appears that the divisions of the Last Glaciation established in north Germany apply to all glaciated regions as far as the Caucasus, and here and there the earlier glaciations also have been subdivided into phases.

c. THE GLACIATIONS OF THE ALPS.

The Alps are the home of the well-known divisions of the Pleistocene, Günz, Mindel, Riss and Würm. These were introduced by Penck and Brückner (1909) in their monumental work on the Ice-age of the Alps and its deposits. It bears testimony to the genius of these two workers that they recognized so long ago that there were four great glaciations. Moreover, Penck estimated surprisingly correctly the relative duration of the intervening interglacials, that between Mindel and Riss being by far the longest (Fig. 16). This estimate has gained in importance in the light of the astronomical theory (p. 166).

Penck and Brückner based their divisions chiefly on the glacifluvial

gravel terraces formed by the waters of the melting glaciers. They recognized two complexes of gravels lying high above the level of the present rivers and called them older and younger *Deckenschotter*. In addition, there are the "*High Terrace*" and the "*Low Terrace*," separated from the Deckenschotter by a considerable interval. The glaciations during which these tracts of gravel were formed received the following names:

Glaciation of the Low Terrace . . .	Würm.
Glaciation of the High Terrace . . .	Riss.
Glaciation of the younger Deckenschotter .	Mindel.
Glaciation of the older Deckenschotter .	Günz.

Of course, Penck and Brückner assigned many moraines to these glaciations, but it must be kept in mind that, primarily, the divisions were based on the more easily identifiable gravel fans and terraces.

The Penck and Brückner chronology was readily adopted in many

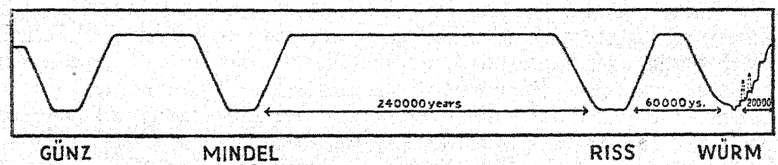


FIG. 16.—Penck's curve of the Ice-age in the Alps (1909), with estimated duration of the Postglacial and the Interglacials.

countries and, unfortunately, only too often applied to insufficiently investigated deposits in a way that can hardly be called scientific. The confusion which has resulted is still one of the chief obstacles to a world-wide relative (and absolute) chronology of the Pleistocene.

EXTENSION OF THE ALPINE GLACIATIONS.—As in the peripheric zone of the Scandinavian area, a belt of weathered and denuded, evidently old, moraines surrounds an inner zone of well-preserved, young moraines. The latter are everywhere connected with the Low Terrace, and there can be no doubt that they belong to the Würmian. Their correlation with the Weichsel glaciation of north Germany is justified on morphological and stratigraphical grounds and has never been contested.

The "old moraines" are generally considered as largely of Rissian age (Woldstedt, 1929, p. 232) or, in Switzerland, of the "Greatest Glaciation," which is probably the equivalent of Riss. Quite recently, however, Knauer (1938*a*) has published evidence for Mindel moraines exceeding the Riss moraines in extension, between the rivers Iller and Salzach. He points out the similarity to parts of north Germany in this respect. Eberl (1930), who made a special study of the area between the Iller and the Lech, found that in the Lech valley Riss was larger than Mindel, though in the Günz and Iller valleys Mindel exceeded Riss. In both cases, however, the differences are small. Thus it appears that the Mindel and Riss glaciations compete for the maximum extension in the forelands of the German Alps, as do Elster and Saale in north Germany (compare percentage figures, p. 54).

Little is known about the extension of the ice-sheet of the Günz glaciation. In Eberl's area it was smaller than Mindel or Riss.

RETREAT STAGES OF THE LAST GLACIATION.—Numerous stages in the retreat of the Würm Glaciation have been distinguished. In many places there is a double belt of terminal moraines, called the outer and inner "Young End-moraines." Penck and Brückner distinguished two major mild oscillations during the retreat (*Laufen* and *Achen*), but abandoned them later. The later halts, or re-advance phases, called *Bühl*, *Gschnitz* and *Daun*, with terminal moraines inside the mountain valleys, are the most Recent phases in the retreat. Bühl has been correlated with the Pomeranian phase by many authors, especially by Penck and Soergel, but Woldstedt (1928*b*, p. 234) has produced serious arguments against this view. Bühl appears much too small to be correlated with a phase of the intensity of the Pomeranian.

DETAILED RELATIVE CHRONOLOGY OF THE ICE-AGE IN THE GERMAN ALPS.—The points mentioned so far have provided the skeleton for the divisions of the Alpine Pleistocene, and also for their correlation with the north German phases. It has to be admitted that, on broad lines, the correlation of Würm with Weichsel (" young moraines " and glacial lakes), Riss with Saale, and Mindel with Elster (the two old bottom moraines with the greatest extension), appears to be reasonable. It is not surprising that there is no undisputed equivalent of Günz in north Germany, this glaciation having been much smaller than the two following.

As in the area of the Scandinavian glaciation, so in the Alpine area, field-work has produced evidence that, in reality, the divisions of the Ice-age are more complicated than is implied by the conventional interpretation of the fourfold Penck and Brückner scheme. Nearly twenty years after the conclusion of the *Alpen im Eiszeitalter*, Eberl and Knauer, independently, found a series of important subphases.

EBERL'S DETAILED CHRONOLOGY.—Eberl (1928*a*, *b*, 1930) studied the glacifluvial terraces and morainic deposits of the glaciers of the Iller and Lech valleys in western Bavaria, and of the three smaller rivers, Günz, Mindel and Wertach. This is the classical area of the Deckenschotter (the Günz and Mindel rivers lent their names to the respective glaciations). The Iller-Lech area is a dissected plateau which, throughout the Pleistocene, has been in a state of gradual uplift, in connection with the rising of the Alps. Erosion, therefore, was intensified, and the phases of glacial and glacifluvial aggradation are more clearly separated than in other areas, where they are obscured by frequent superposition.

Eberl found that the Low Terrace, High Terrace, and the Deckenschotter are composite formations, each comprising several phases due to fluctuations of the ice-margin. He followed the individual tracts of glacifluvial gravel upstream until the gravels began to contain an increasing proportion of unstratified moraine, and finally were replaced more or less entirely by morainic material. In this manner he was able to reconstruct the ice-margins of phases the superficial features of which had been completely obliterated by denudation.

THE LOW TERRACE.—The Low Terrace is divided into three phases. The second of these corresponds to the outer belt of terminal moraines of the Last Glaciation. Its ice passed over the moraine of the first phase, which was smaller, eroding and transforming it into a group of hillocks of the type called drumlin. The third and latest phase of the Low Terrace is

connected with a moraine inside the outer belt. The subdivision of Würm into three phases thus is evident. The second phase was the largest, and built up the conspicuous "Young End-moraines."

THE HIGH TERRACE.—The High Terrace is connected with the moraines called Riss by Penck. In Eberl's area it consists of two distinct glacifluvial terraces, each of which is linked with a set of moraines. Eberl emphasizes the fact that this knowledge is not new, Penck, Troll, Schmidle and others having recognized before him the bipartition of the High Terrace.

Eberl found that the moraines of his second Riss lie inside those of the first phase, but the two belts are always closely grouped together. He also found evidence suggesting a re-advance during the retreat of Riss 2.

THE YOUNGER DECKENSCHOTTER.—Eberl distinguishes a large number of phases in the Deckenschotter group of aggradations. Yet his divisions are nothing but a refinement of Penck's original divisions.

The younger Deckenschotter, or Mindel, is renamed by Eberl and called *Altterrasse* ("Old Terrace"). It is composed of two phases, the later of which is more distinct and connected with the moraines generally defined as those of the Mindel Glaciation. The earlier Altterrasse is separated from the later by a period of erosion and weathering. This shows that the corresponding glacial phases cannot have been mere sub-phases of a single major phase; they were separated by a prolonged period of mild climate. The moraine with which the earlier Altterrasse is connected lies inside the morainic belt of the later Mindel; Mindel 1 was smaller than Mindel 2.

THE OLDER DECKENSCHOTTER.—The older Deckenschotter has been subdivided by Eberl into seven stages. Only the two latest of these, however, are to be identified with Penck's Günz-Deckenschotter, and Eberl uses for them the special term *Deckterrasse* ("Cover Terrace"). The younger Deckterrasse is clearly linked with a moraine, inside the belt of the later moraines of Mindel age. The older Deckterrasse can be followed upstream until it assumes the characters of a cone of transition to a moraine, but the material of the terminal moraine itself is not preserved. From the position of this cone, however, the terminal moraine of Günz 1 must have been situated inside that of Günz 2.

Thus, each of the following five glacial phases was larger than the preceding: Günz 1, Günz 2, Mindel 1, Mindel 2, Riss 1. This need not, however, apply to other districts.

THE PRE-GÜNZIAN DECKENSCHOTTER.—Having eliminated all those gravel-spreads which could conceivably form part of the two Günzian Deckenschotters, or Deckterrassen, Eberl was confronted with a considerable number of other occurrences of gravels of the Deckenschotter type which required an explanation. They could not possibly be later than Günz, and did not belong to the Günzian complex either.

Eberl distinguishes five such phases, of which three are called the *Donau* (Danube) *stages*. These gravels, though evidently very old, still have a glacifluvial character. Certain morainic deposits, observed underneath the ground moraine of Günz 1, may be contemporaneous with one of the Donau stages. It is also claimed that there are deposits of weathered loess which have to be correlated with the Donau stages.

The Donau gravels of the Iller-Lech area find a counterpart in the pre-Günzian gravels of the country west of Basle, the *Sundgau gravels*

(Gutzwiller, 1912; van Wervecke, 1924). They, too, are considered as glacifluvial by the authors mentioned.

Earliest Phases.—The two earliest gravel deposits differ petrologically from all the later deposits, since they contain a larger amount of crystalline pebbles than do the later deposits. The *Staufenberg gravels* are separated from the Donau stages by an erosional cliff. Eberl is not certain about their glacifluvial origin. The *Ottobeuren gravels* are the highest known gravel deposits of the Iller-Lech area. They are certainly not of glacifluvial origin, but purely fluviatile, and of a Pliocene aspect.

Eberl's Relative Chronology: Summary.—From the last phase of Würm back to the first phase of Riss, Eberl's subdivisions agree with those of several other recent workers on the Alpine Pleistocene. His chief merit is the close study of the Deckenschotter complex. This produced several hitherto overlooked glacial or other aggradation phases, which find a counterpart in certain terraces of the periglacial area, as will be seen later. Eberl's subdivisions of the Deckenschotter are included in the correlation table, Fig. 17.

Knauer's Chronology.—In the same year as Eberl, Knauer (1928) reported on the discovery of subdivisions in the Alpine Pleistocene. He investigated the eastward continuation of Eberl's district, the Ammer Lake Würm Lake area and the river Isar. He was able to identify:

V.	Würm,	phase II*c* (halt during retreat).
	,,	phase II*b* ,, ,,
	,,	phase II*a* (maximum extension).
	,,	phase I (halt during advance).
IV.	Riss,	phase *b* (later moraines and gravels).
	,,	phase *a* (earlier moraines and gravels).
III.	Mindel	phase *b* (later gravels and Nagelfluh).
	,,	phase *a* (earlier gravels and Nagelfluh).
II.	Günz (Nagelfluh).	
I.	Stoffersberg Nagelfluh (early Pleistocene or Pliocene).	

Knauer's divisions are simpler than those of Eberl. He distinguishes two moraines of Rissian age, of which the earlier is superimposed on a deeply weathered moraine regarded as Mindel 2. This, in turn, covers a weathered loess (Mindel 1), and the entire section rests on deeply weathered Deckenschotter, possibly of Günzian age (Knauer, 1938*a*). The number of glacial phases again exceeds the number four originally postulated by Penck and Brückner, whose divisions now assume the rank of major units ("glaciations") composed of several minor phases ("glacial phases").

From the Lech to the Isar such subdivisions have been established. This is an important result, no matter how the individual phases will eventually be correlated with those of adjacent districts, since the number four of the Alpine glaciations has been used as an argument against a more detailed chronology of the Pleistocene. It has now become apparent that the numerous cold phases evidenced by loesses and gravel terraces in the periglacial area of central Europe have their counterparts in the phases of the Alpine glaciations.

The PROBLEM OF WÜRM 1 IN BAVARIA.—Eberl as well as Knauer consider the second stage of Würm as the largest. In other words, they recognize an oscillation during the *advance* of the Würm ice and call it Würm 1. Troll, however, another authority on the glacial deposits of the forelands of the Alps, does not agree with this view, and a controversy on the subject has developed and is still continuing (Knauer, 1935, 1937, 1938*b*; Troll, 1936). Knauer's attempt to interpret in the same manner conditions in north Germany may be considered as a failure (see p. 39, and Knauer, 1937, Gripp, 1940).

The question whether the first phase of Würm was larger or smaller than the second does not affect the detailed chronology as such, but it introduces a serious uncertainty into the correlation of the Alpine phases of Würm with the established cold phases of the periglacial area and with the north German phases. It is necessary, therefore, to consider this question further. This will be done after a short review of the Swiss evidence.

Apart from the problematical advance stage, the major phases of the Würm glaciation are considered as fairly clear. There are three, each successively smaller than the preceding. They have been named as follows :

	Troll, 1926 (Bavaria).	Troll, 1925 (Lake Constance).	Hug, 1917 (Switzerland).
Third phase	Ölkofen	Singen	Zürich
Second phase	Ebersberg	Diessenhofen	Schlieren
First phase	Kirchseeon	Schaffhausen	Killwangen

Troll (1925) proposed for general use the terms of the Lake Constance area, but Woldstedt (1928*b*) prefers the Swiss terms of the Lake Zürich region. Woldstedt is inclined to regard these three phases as equivalents of the Brandenburg, Frankfurt and Pomeranian phases in north Germany, and finds support for his view in the correspondence of the relative peripheric positions of these phases. This point, too, will be discussed later (p. 172).

SWISS CHRONOLOGY.—In Switzerland it was found that the Würm, Mindel and Günz glaciations are represented in much the same way as in the German Alps, namely, Würm by fresh moraines and the Low Terrace, and Mindel and Günz by stages of Deckenschotter. The High Terrace, however, is held by some not to be connected with moraines, but a Middle Terrace has been distinguished which is linked with the moraines of the so-called Greatest Glaciation (Heim, 1919). This glaciation has been correlated by most authors with the Riss of the German Alps, but Soergel (1919) considers it as the equivalent of the fifth glacial terrace and the Younger Loess I of the periglacial area.

In recent years extensive research has been carried out by P. Beck (1933, 1936, 1937, 1939), chiefly on the Aare Glacier which filled the valley now occupied by the lakes of Thun and Brienz. He discarded the " Greatest Glaciation " as being based on insufficient evidence (Heim already identified it occasionally with Riss), but found two distinct glacial phases intercalated between the Deckenschotter and the High Terrace. Beck's chronology is as follows (after Beck, 1937) :

Late Glacial.		Three stages.
Würm	Zürich . . .	Inner Young End-moraines, mostly enclosing lake basins, and lowest Low Terrace.
	Schlieren . .	Middle Young End-moraines and middle Low Terrace.
	Killwangen . .	Outer Young End-moraines and main Low Terrace.
Riss-Würm Interglacial .		Gravels.
Riss	Late-Riss . . .	Inner belt of Old moraines and lower High Terrace.
	Great-Riss . .	Outer belt of Old moraines, maximum glaciation, and upper High Terrace.
Glütsch-Riss Interglacial .		Channel-gravels below Riss moraines.
Glütsch		Moraines intercalated in Channel-gravels.
Kander-Glütsch Interglacial .		Channel-gravels below Glütsch moraine.
Kander		Moraine between Channel-gravels and rock.
Mindel-Kander Interglacial .		Erosion of channel-like valleys.
Mindel		Moraines connected with lower, younger Deckenschotter.
Günz-Mindel Interglacial .		Erosion.
Günz		Moraines connected with upper, older Deckenschotter.
Pregünz		Very high, intensely weathered gravels of Sundgau.
Astian-Plaisancian (Tertiary).		Marine clays and sands with fossils in southern Alps.

One notices that Beck has retained the terms Günz and Mindel for two glacial phases or glaciations of the Deckenschotter. The Deckenschotter period is succeeded by a period of erosion, resulting in a deepening of the valleys to much below the present level. After this, two glacial phases occurred which have not yet been identified in other districts of the Alps. They are called Kander and Glütsch, and their moraines, together with gravels, filled the valleys up to the level of the High Terrace. The glacial phases Glütsch and Kander appear to have been less extensive than the following, Riss. According to Beck, Riss *is* connected with the High Terrace in Penck's sense, and it is divided into two phases. The Würm glaciation is divided into the usual three phases, from the maximum extension onwards. Eberl's advance-phase of Würm has not yet been identified in Switzerland.

Beck distinguishes six major glaciations, with at least nine recognizable phases. Those of the Würm and Riss glaciations are essentially the same as those further east, except for the absence of the advance-phase of Würm. Beck did not subdivide the Deckenschotter complex. His discovery of the glacial phases Kander and Glütsch, however, is remarkable. They post-date the Deckenschotter and the great erosion of the valleys, but ante-date Riss.

RHINE TERRACES BETWEEN CONSTANCE AND BASLE.—From the preceding review it is clear that the evidence for the succession of glacial phases in the Alps embraces two obscure points of major significance, namely, (*a*) that of the phases of Würm, and (*b*) that of the relation of Riss to the preceding phases, Glütsch and Kander, which have been claimed by Beck.

In the hope of throwing some measure of light on these problems the present author, jointly with Mr. Day Kimball, has undertaken an analysis of the terraces of a crucial and well-studied area, that of the Rhine from the point where it leaves Lake Constance down to the knee at Basle, where it enters the rift valley between the Vosges and the Black Forest. The details of this investigation are too complex to be given here; they are being published elsewhere (Zeuner and Kimball, 1944). The main results, which are corroborated by those of several other investigators, notably of Erb (1936), are as follows:

(*a*) The "Greatest Glaciation" is connected with the Low High Terrace (*i.e.* in part former Middle Terrace) and, therefore, Riss. The interpretation of the Greatest Glaciation as the first phase of Würm (Soergel, 1919) cannot be upheld.

(*b*) The Upper High Terrace (*i.e.* the ordinary High Terrace of most authors) appears to contain the moraines of a relatively small glaciation (first noted by Heim, 1919), which on the evidence of sections at Lake Zürich (Hug, 1932; Beck, 1933) is Beck's Glütsch phase. Since the Upper High Terrace has always been included in the "Riss" complex, the Glütsch phase is possibly nothing but the first, smaller, phase of Riss, and the duplication of the extreme moraines of the "Greater" Riss, observed by Eberl and Beck, may be the result of a minor oscillation during Riss 2. This, at any rate, is suggested by the Rhine terraces.

(*c*) Whatever the outcome of the controversy over the moraines, as given under (*b*), may eventually be, *two* distinct terraces of the Riss complex have been recognized in the Rhine, as in the Aare by Beck, in the Iller-Lech area by Eberl, and previously by Penck and others along the northern fringe of the Alps.

With respect to the Low Terrace group, which connects with the outwash fans of numerous terminal moraines of the Last Glaciation, it has been found that—

(*d*) Three independent Low Terraces exist, which are separated by two phases of intense erosion. They suggest three phases of the Last Glaciation.

(*e*) The High Low Terrace comes from moraines of the Schaffhausen phase, the Middle Low Terrace from those of the Diessenhofen (Scharenwald) phase, and the Low Low Terrace from those of the Stein-Singen phase, the first of these being the largest, the last the smallest. This result supports Troll rather than Eberl or Knauer.

GLACIAL PHASES OF THE ALPS: SUMMARY.—It must be emphasized that the disagreement of the various workers on Alpine glaciations is chiefly confined to the question of the relative extension of the glaciers during the respective phases. Their *number*, which is based on the number of aggradation terraces, is much less disputed. The following seems to be a fair summary of the present state of our knowledge:

(1) There are three Low Terraces connected with moraines of fresh topography and, therefore, three main phases of the Last Glaciation (Würm).

(2) There are two High Terraces and, therefore, two main phases of the Penultimate Glaciation (Riss).

(3) There are suggestions of minor phases of Riss.

(4) Riss was preceded by a period of very deep valley-cutting during which the main features of the present-day topography were established. This is the Great Interglacial of Penck and Brückner. It was presumably of very long duration.

(5) In Switzerland, Beck has evidence of two minor advances of the ice following the main valley-cutting but preceding the glaciation of the Lower High Terrace (Glütsch and Kander phases). Of these, the earlier (Kander) is very obscure, whilst the later is possibly synonymous with the first phase of Riss, apparently being the glaciation of the Upper High Terrace as defined in the Rhine area.

(6) The Deckenschotter comprises more than two glacial phases.

(7) The Antepenultimate Glaciation (Mindel) was approximately as large as Riss, though in many districts it remained somewhat smaller. It had two phases.

(8) The Early Glaciation (Günz) was a smaller glaciation, perhaps comparable in size with Würm, but its moraines are little known so far. It also had two phases.

(9) The higher and earlier portion of the Deckenschotter comprises five more phases of aggradation, four of which are regarded as glacifluvial by Eberl.

If one pays attention to the relative extension of the phases of the Last Glaciation one finds that it is still a matter of controversy in the Alps, as in the Scandinavian area of glaciation. Here and there the problem is the same, namely, whether the first of the three phases was larger or smaller than the second. In the Rhine area, Würm 1 (Schaffhausen Phase) was larger than Würm 2 (Diessenhofen Phase), and this larger than Würm 3 (Stein-Singen Phase). These conditions are comparable with the Warthe (Fläming moraine), Weichsel (Brandenburgian moraine) and Pomeranian phases of North Germany, but in Bavaria Würm 1 is regarded as smaller than Würm 2 by Eberl and Knauer, but not by Troll, rendering it as elusive as the equivalents of the Warthe phase in Jutland.

A similar uncertainty is attached to the two Alpine phases of the Penultimate Glaciation. In the Rhine area Riss 2 appears to have been larger than Riss 1, but in Bavaria, for instance, Riss 1 is said to have been larger than Riss 2, though only slightly so. The Rhine area is in this respect again reminiscent of north Germany.

In view of the uncertainties attached to the Alpine phases, it is inadvisable to continue applying the Alpine terms to other areas of glaciation. In the present context, therefore, Würm, Riss, Mindel and Günz, in the *unabbreviated* form, designate phases of the Alpine area of glaciation. For general purposes the terms Last Glaciation, Penultimate Glaciation, Antepenultimate Glaciation and Early Glaciation will be used.

D. NORTH AMERICA.

The North American area of glaciation was much larger than the European. It has been admirably studied by many workers both in Canada

and the United States, and several comprehensive publications have appeared (for instance, G. F. Wright, 1911; Chamberlain and Salisbury, 1906; Coleman, 1926, 1941; Antevs, 1928*).

As in Europe, the glacial period in North America comprises several separate glaciations. The kind of evidence afforded for the interglacials is the same in both continents; there are interglacial fossiliferous beds as well as weathering horizons. The latter have received more attention in North America than in Europe, and a special term, *gumbotil*, is in use to designate decalcified, loamy weathering soils, chiefly formed on boulder-clay.

North American Divisions.—The following divisions have been distinguished:

Wisconsin Glaciation { Late phase. / Middle phase. / Early phase. }
Peorian Interglacial.
Iowan Glaciation.
Sangamon Interglacial.
Illinoian Glaciation.
Yarmouth Interglacial.
Kansan Glaciation.
Aftonian Interglacial.
Nebraskan Glaciation.

The deposits of the Wisconsin Glaciation exhibit the same fresh morphological features as those of the Weichsel Glaciation in Europe, and a correlation of these with the Wisconsin is considered as justified by many authors.

Problem of the Iowan.—The three earliest glaciations (Nebraskan, Kansan, Illinoian) are represented by sheets of boulder-clay, well separated by gumbotils. Regarding the Iowan, however, opinions are not unanimous. Its boulder-clay rests on a gumbotil and is covered by a loess (Peorian loess). According to Kay (1928), weathering affected the loess and the moraine together, so that the formation of this loess appears to have followed closely the formation of the boulder-clay. The loess, in turn, is covered by deposits of early Wisconsin age in many sections, with no, or inconsiderable, weathering of the surface of the loess. Kay (1928) and Woldstedt (1928*b*, 1929, 1930), therefore, suggest that the Iowan is the earliest phase of the Wisconsin Glaciation.

Leverett (1910, 1926), however, has attempted to link the Iowan with the preceding glaciation, the Illinoian. He holds the view that during the Illinoian the centre of glaciation was displaced in a westward direction and that the Iowan is nothing but the western equivalent of the Illinoian. This view would find support in the fact that apparently nowhere is the Iowan clearly superimposed upon Illinoian moraine.

There is, however, the section of Farm Creek, near Peoria, which rests on undisputed Illinoian boulder-clay, and suggests that the Iowan was, after all, a fairly independent glacial phase. The section (Leighton, 1926) is as follows:

* A good short summary is found in Woldstedt, 1929.

	Soil / Leached loess / Fresh loess	$4\frac{1}{2}$–$7\frac{1}{2}$ ft.
Wisconsin :	Bloomington gravel	0–4 ft.
	Shelbiville till	32 ft.
	,, unconformity.	
Peorian :	Loess, with humus streak 2 in. thick about 10 in. below the till	6 ft.
Sangamon :	Old soil	1–$1\frac{1}{2}$ ft.
	Loess-like silt (weathered loess)	7–8 ft.
Illinoian :	Gumbotil	4 ft.
	Grades into calcareous till.	

The Illinoian boulder-clay is deeply weathered. A loess rests on it, the uppermost one or two feet of which are transformed into a soil. It is covered by the Peorian loess, on which follows the Wisconsin boulder-clay with an unconformity caused by the denudational activity of the ice. The intense weathering after the Illinoian, and the less intense but distinct weathering preceding the Peorian loess, individualize the intermediate loess, which is called Sangamon by Leighton but which Woldstedt prefers to call Iowan loess. It indicates a dry phase intervening between the Illinoian and Wisconsin.

Subdivisions of the Wisconsin.—The subdivisions of the Last Glaciation of North America are of particular interest as they offer a parallel to the development of the Weichsel Glaciation of north Europe. A number of terminal moraines have been distinguished. It is best to use the names established on a line from New York to the Hudson Bay. This line is famous for the varve-countings carried out by Antevs (1928). The chief morainic stages, from the latest to the earliest, are as follows :

Cochrane, Ontario.
Montreal River, Ontario.
Mattawa, Ontario.
Stony Lake, Ontario.
St. Johnsbury, Vermont.
Hartford, Connecticut.
Harbor Hill.
Ronkonkoma on Long Island.

The Harbor Hill and Ronkonkoma stages lie very close together and have mostly been considered as being close in the chronological sense also. Recently, however, Bryan and Ray (1940) have suggested, on the strength of differences in weathering and preservation, that the Ronkonkoma is considerably older than the Harbor Hill stage, and they tentatively correlate the former with the Iowan. The Harbor Hill moraine would thus be the maximum of the Wisconsin, and the Peorian of the Farm Creek section would intervene between the Ronkonkoma and Harbor Hill stages.

Of the further stages of retreat, the St. Johnsbury moraine is of special importance.

Loess occurs on morainic deposits of the earlier phases of the Wisconsin glaciation.

Correlation of North America with Europe.—The first attempt at a comparison of the North American Pleistocene with that of Europe was made by Leverett (1910). Having visited the Alpine and Scandinavian areas, he correlated the Wisconsin with Würm, the Kansan with Mindel and the Nebraskan with Günz, whilst the Illinoian appeared to him older than Riss. His comparison with North Germany includes an attempt to correlate the lower of the two old boulder-clays of north Germany (now called Elster) with Günz, which is certainly not in keeping with the evidence ; but he agreed that the area of the Weichsel Glaciation corresponds to at least part of the Wisconsin. It is interesting to note that he was inclined to regard part of the Alpine Riss and part of the Saale area of north Germany as possible equivalents of the earlier Wisconsin. This shows, from the European standpoint, that, at that time, the American Wisconsin comprised stages which are older than Weichsel, and this recalls once more the question of what the Iowan and the Ronkonkoma stage really are.

More recently Woldstedt (1930) visited North America with the view to investigating the possibilities of a correlation, especially with north Germany. He found that the middle and late Wisconsin compare well with Weichsel or Würm, but the early Wisconsin appears to be older than the Weichsel Glaciation. Woldstedt suggests that the Iowan is either the equivalent of the Warthe phase, or of the Middle Bed of the Last Interglacial of Denmark (which, however was of little intensity, see p. 35). The Illinoian compares well with Saale or Riss. More doubtful appears to him the correlation of the Kansan and Nebraskan. There is only one certain pre-Saale glaciation in north Germany, but there are two pre-Rissian glaciations in the Alps. One is tempted to correlate Kansan and Nebraskan with Mindel and Günz respectively (as done by Leverett), and if Elster is contemporary with Mindel, it would also be the equivalent of the Kansan. In the state of preservation, however, Elster resembles the Nebraskan rather than the Kansan, but it is implied in Woldstedt's words that he considers the former correlation as the more probable.

The Iowan occupies much the same position as does Warthe in north Germany. It has been annexed by some to the preceding glaciation, by others to the following. This, indeed, suggests that they are equivalents of one another. Bryan also holds this view. If Bryan and Ray are correct in considering the Ronkonkoma moraine as Iowan, the resemblance of the Iowan with the Warthe stage would be very close. Recent research has supplied evidence for Warthe being closer to Weichsel than to Saale, and for the Iowan being closer to the Wisconsin than to the Illinoian.*

If the Ronkonkoma moraine is of Iowan age, the Harbor Hill stage would represent the maximum of the Wisconsin Glaciation and, therefore, correspond to the Brandenburgian of north Germany. This is suggested by Bryan and Ray (1940). These authors are further inclined to correlate the St. Johnsbury stage with the Pomeranian, and the Cochrane stage (though with a query) with the Fennoscandian halt.

* On correlation of North America and Europe, see also Girmounsky (1931).

E. RELATIVE CHRONOLOGY OF THE MORAINIC AREAS OF SCANDINAVIA, ALPS AND NORTH AMERICA: GENERAL SUMMARY AND CORRELATION.

In all three areas under consideration, unambiguous evidence has proved the multiplicity of glacial phases. These are summarized in the table (Fig. 17).

SCANDINAVIAN AREA.—In the Scandinavian area, and in north Germany in particular, three great glaciations can be distinguished with certainty (Elster, Saale, Weichsel). To these has to be added the Warthe Phase, which preceded Weichsel, either as an independent glaciation or as a glacial phase. Weichsel, from its maximum onwards, shows three major halts of the ice-margin (Brandenburgian, Frankfurt, Pomeranian). There is, in Denmark, evidence for a minor cold phase which occurred during the Last Interglacial. Glacial phases preceding Elster, the earliest well-established phase, have been postulated, but are still doubtful.

ALPINE AREA.—In the Alps four great glaciations have been distinguished. The last three (Mindel, Riss and Würm) agree in many respects with Elster, Saale and Weichsel of north Germany. The Günz Glaciation of the Alps has not yet been identified in the Scandinavian area, unless it is represented by one of the problematical pre-Elster phases.

The Alpine glaciations, Riss, Mindel and Günz, each consist of two glacial phases which are separated by interstadials with a mild climate. Würm appears to comprise three such phases. Several glacial phases preceding Günz have been recognized, and one or two further minor phases may have preceded Riss in Switzerland.

COMBINATION OF THE TWO EUROPEAN AREAS.—Thus, evidence in north Germany and in the Alps suggests the following succession of cold phases in temperate Europe:

The transition from the Pliocene to the Pleistocene is marked by at least three cold phases.

The Early Glaciation comprises two phases.

The Antepenultimate Glaciation comprises two phases in the Alps.

The following Great Interglacial, which was of long duration and during which considerable erosion took place, possibly includes one or two minor glacial phases.

The Penultimate Glaciation comprises two phases in the Alps. It was the largest glaciation in many districts, though it was locally exceeded by the Antepenultimate Glaciation.

During the Last Interglacial a cold oscillation occurred, but the climatic effects suggest that no large ice-sheet was formed.

The Warthe phase of the Scandinavian area is either the first phase of the Last Glaciation or a late phase of the Penultimate Glaciation. It might correspond to a relatively small advance phase of the Last Glaciation observed in the Alps, or to a retreat phase of Riss observed by Eberl only. To the present author, however, it appears more likely that the Schaffhausen Phase of the Rhine Glacier is the Alpine equivalent of the Warthe Phase.

PENCK & BR.	ALPINE AREA		SCANDINAVIAN AREA		GENERAL TERMINOLOGY	NORTH AMERICAN AREA	
	ONE OF THE STAGES INSIDE THE MOUNTAINS		FENNOSCANDIAN MORAINE	WEICHSEL	LAST GLACIATION	?COCHRANE STAGE	WISCONSIN
WÜRM	LOW LOW TERRACE = ZÜRICH = STEIN PHASE		POMERANIAN MORAINE		LGl 3	ST. JOHNSBURY MORAINE	
	MIDDLE LOW TERRACE = DIESSENHOFEN PHASE		b. FRANKFURT-POSEN a. BRANDENBURGIAN		LGl 2	HARBOR HILL MORAINE	
						PEORIAN INTERSTADIAL	
	HIGH LOW TERRACE = SCHAFFHAUSEN PHASE		FLÄMING OR WARTHE PHASE		LGl 1	IOWAN, ? = RONKONKOMA	
		LAST INTERGL.	SKARUMHEDE SERIES	LAST INTERGL.	LIgl LAST INTERGLACIAL	SANGAMON INTERGLACIAL	
			DANISH MIDDLE BED				
			EEM SERIES				
RISS	LOW HIGH TERRACE = GREATEST GLACIATION		SAALE MORAINE		PGl 2 PENULTIMATE GLACIATION	ILLINOIAN	
	UPPER HIGH TERRACE ? = GLÜTSCH PHASE				PGl 1		
		GREAT INTERGL.	GREAT INTERGLACIAL		PIgl PEN-ULTIMATE INTERGLACIAL	YARMOUTH INTERGLACIAL	
	?GLÜTSCH OF BECK						
	KANDER OF BECK						
MINDEL	LATE ALTTERRASSE	DECKENSCHOTTER	ELSTER MORAINE		ApGl 2 ANTE-PENULTIMATE GLACIATION	KANSAN	
	EARLY ALTTERRASSE			v. WERVECKE'S PRE-ELSTER MORAINES??	ApGl 1		
					ApIgl ANTEPEN. INTERG.	AFTONIAN INTERGLACIAL	
GÜNZ	LOWER DECKTERRASSE				EGl 2 EARLY GLACIATION	?NEBRASKAN	
	UPPER DECKTERRASSE				EGl 1		
	DONAU GRAVEL III						
	DONAU GRAVEL II						
	DONAU GRAVEL I						
	STAUFENBERG GRAVEL						
	OTTOBEUREN GRAVEL						

FIG. 17.—Correlation of the Pleistocene climatic phases of the Alpine, Scandinavian and North American areas of glaciation, and their general terminology. For controversial points, compare text. This correlation is not to be regarded as final; it represents the most probable interpretation of the sequences as known in 1943.

The Last Glaciation comprises three phases. It is uncertain, however, whether the first or the second was the largest.

The radial extension of the glaciers of the Iller-Lech area of the Alps is compared with that of the Scandinavian ice-sheet in the following table. The figures for the former have been based on Eberl's data, and represent the relative distances from the nevées in the Lechtal Alps to the terminal moraines. Occasional maximum advances are given in brackets. The figures for north Germany are the same as on p. 38; they are added for the purpose of comparison, and the correlation of the phases need not be correct. In the Alps, Mindel 2 was taken as the unit, in the Scandinavian area, Elster.

Würm 3	85·5%	Pomeranian	87·5%.
Würm 2	95·5 (–102)%.	Weichsel	92·5%.
Würm 1	90% (Rhine, *ca.* 105%).	Warthe	95%.
Riss 2	92·5–98·5 (–107)%.	Saale	97·5–102·5%.
Riss 1	95–110 (–130)%.		
Mindel 2	100%.	Elster	100%.
Mindel 1	95–96%.		
Günz 2	90%.		
Günz 1	81%.		

North American Area.—In North America five glaciations have been distinguished. The last, the Wisconsin, resembles Würm = Weichsel in so many respects that it has been correlated with these, as an entity as well as with its individual subphases. The Iowan occupies the same position in North America as does the Warthe phase in north Germany. The majority of authors now regard the Iowan as a forerunner of the Wisconsin, and some correlate it definitely with the Warthe phase.

The earlier glaciations, the Illinoian, Kansan and Nebraskan, are regarded as the equivalents of Riss = Saale, Mindel = Elster, and Günz, respectively.

The resemblance which undoubtedly exists between the North American divisions and those of north Europe and the Alps has led to the assumption that the various glacial phases of North America were contemporary with those of Europe. Many observations support this view, but it must be admitted that definite evidence of contemporaneity has not yet been produced, except perhaps for the latter part of the Last Glaciation (by means of varve countings).

The morainic and glacifluvial subdivisions of the Pleistocene, both in Europe and North America, suggest intense fluctuations of the climate. The rhythm of these fluctuations appears to have been peculiar; there were two early and two late glaciations, separated by a long interval (the Great Interglacial), and each of these four glaciations appears to comprise two or three distinct glacial phases separated by interstadials with a milder climate. In addition, a few minor cold phases occurred during the interglacials, and several very early glacial phases preceded the first commonly accepted glaciation.

We shall now turn our attention to the periglacial area, in order to find out how far the relative chronology suggested by the morainic areas is supported by evidence from the zone the climate of which was directly affected by the glaciations.

CHAPTER III

THE PERIGLACIAL AREA OF CONTINENTAL EUROPE

A. THE PERIGLACIAL ZONE.

Limits of the Periglacial Zone.—Areas the climate of which was influenced by the cooling effect of the ice-sheets were of considerable extent, both in Europe and North America. The limits of these *periglacial areas* towards the ice were, of course, well defined by the margin of the ice itself, but it is more difficult to draw a line between the zones which show all the characteristics of a periglacial climate and those which were less intensely affected. As regards Europe, it is known that in the Mediterranean area the typical Mediterranean fauna and flora was, during the glacial phases, largely replaced by the fauna and flora of the deciduous forest zone of temperate Europe; yet it is evidently not advisable to include the Mediterranean in the periglacial zone for this reason.

The term *periglacial* has generally been confined to the effects of heavy frost. The *periglacial zone*, or *area*, therefore, should be regarded as that zone surrounding an ice-sheet, in which the cooling effect of the ice produced a *frost climate*. At the present day frost climates characterize the polar region, the tundra of north Europe and the high mountains, where the average temperature is below freezing-point for a large part of the year and where the warmest month averages less than + 10° C. (50° F.). The July isotherm of + 10° C. roughly coincides with the northern limit of forest growth.

At its northern edge the belt of forests is replaced by the type of environment called *tundra*, the zone of dwarf shrubs and mosses and of abundant peat formation. Under glacial conditions the tundra adjoined the ice, and it was combined with barren tracts of glacifluvial deposits, the *sanders*, and with patches of freshly deposited moraine. The cover of vegetation was by no means complete but, on the whole, conditions in the tundra and sander zone of a periglacial area resembled those of the tundra zone of the present day. For short, the term *tundra zone* is applied to the tundra and sander belt of a periglacial area.

Unlike the present tundra zone, which passes into the zone of temperate forests, the tundra zone surrounding a large ice-sheet passed into the belt of dry and cold steppe in which the loess was deposited (see p. 4), and the loess zone in turn gradually passed into the zone of the temperate forest. It has been demonstrated before (p. 13) that the loess belt was characterized by permanently frozen subsoil, and the temperature of the warmest month appears not to have exceeded + 10° C. (for details, compare Zeuner, 1937*a*).

It is appropriate, therefore, to include in the periglacial area the loess belt as well as the tundra belt.

At the present day, the transition from tundra to forest is marked by a zone in which coniferous forest grows on tjæle. This type of forest is called *taiga*. It has not yet been possible to ascertain whether taiga formed the edge of the loess-belt. Taiga requires a short summer with average temperature above + 10° C., but the remainder of the year is very cold. In geological sections the taiga would hardly leave other evidence than that of permanently frozen subsoil. For this reason it is advisable to consider as part of the periglacial area any taiga that might have existed at the margin of the loess belt.

Taiga passes into the zone of temperate deciduous forest. This zone was removed to the southern portion of Europe under the influence of the glacial phases, but its climate, though modified in some respects, retained its temperate character. The line between the periglacial and temperate zones during the glacial phases, therefore, is best drawn where the evidence of permanently frozen subsoil ceases, including the entire belt of loess deposition.

The periglacial area has furnished by far the most complete evidence of climatic oscillations during the Pleistocene. A locality situated in this zone experienced a temperate climate (with forests, chemical weathering and erosion) during the interglacials and interstadials, and a frost climate (with loess steppe or tundra, mechanical weathering and aggradation) during the glacial phases, and it even might occasionally have been covered by deposits of the ice itself during exceptional advance-phases.

B. THE RIVER TERRACES OF CENTRAL EUROPE.

River Terraces of Thuringia.—The rivers of the periglacial area with their systems of climatic terraces (see p. 25) have supplied the most detailed relative chronology. Thuringia is the classical district in this respect.

Here Soergel (1924) succeeded in establishing that, in the course of the Ice-age, the river Ilm passed through ten phases of aggradation of gravel terraces, with intercalated phases of erosion. The aggradations proved to have begun while the climate was comparatively mild, but the upper portions of the larger aggradations showed evidence of decidedly cold conditions, and the top beds of the gravels pass either into a loess or into a varved clay which, in turn, was covered by a boulder-clay. This conformable superposition of glacial deposits on gravel terraces is of the greatest importance, since it provides the exact position of the two earlier Scandinavian glaciations (Elster and Saale) relative to the system of river terraces.

In 1933, Toepfer, starting from investigations by Naumann and Picard (1915), confirmed many of Soergel's results for the middle course of the River Saale, of which the Ilm is a tributary. He found that the Penultimate or Saale Glaciation was actually one aggradation phase later then Soergel thought. The Thuringian river terraces supply the following succession in descending order as the terraces occur on the slopes of the valleys. It may be regarded as the prototype of the terrace sequence of central Europe.

Preglacial terrace VII.
Preglacial terrace VI.

Preglacial terrace V.
Preglacial terrace IV.
Preglacial terrace III.
Preglacial terrace II.
Preglacial terrace I, covered conformably by deposits of the Elster Glaciation (at Zwätzen, near Jena).
Glacial terrace 1, highest terrace containing Scandinavian erratics. Not covered by loess.
Glacial terrace 2, covered conformably by an older loess and disconformably by deposits of the Saale Glaciation.
Glacial terrace 3, covered conformably by deposits of the Saale Glaciation in the district of Halle and Weissenfels.
Glacial terrace 4, without loess.
Glacial terrace 5, grading into Younger Loess 1.
Glacial terrace 6, grading into Younger Loess 2.
Floodplain.

It must be noted that the term *preglacial* does not mean pre-Pleistocene, but merely previous to the first transgression of ice over the district. All terraces formed after this event are called *glacial*. These terms are not very fortunate, because of the ambiguities involved.

Cold climatic conditions have been established, either geologically or faunistically, for all these aggradations, except glacial terraces 1 and 4.

Soergel is inclined to consider the floodplain gravels as aggraded during a latest cold phase, but no definite proof has been obtained by him (Soergel, 1939, p. 171, footnote), and he admits other alternatives. Grahmann, however, regards the floodplain gravels of rivers in Saxony as a cold aggradation on the evidence of peats with a cold flora found beneath the modern floodloam (Grahmann, 1928, p. 146).

SAALE TERRACES BETWEEN WEISSENFELS AND HALLE.*—Downstream of Naumburg, to which town Toepfer, Naumann and Picard followed the terraces of the Saale, the river enters the North German Lowlands, where

Siegert and Weissermel.	*Toepfer.*
1st preglacial terrace	? Preglacial T. IV.
2nd preglacial terrace	? Preglacial T. III.
3rd preglacial terrace	Preglacial T. II.
4th preglacial terrace, conformably covered with thick deposits of Antepenultimate (Elster) Glaciation	Preglacial T. I.
Upper Main Terrace	Glacial T. 1 and/or 2.
Lower Main Terrace, conformably covered with thick deposits of Penultimate (Saale) Glaciation	Glacial T. 3.
2nd Interglacial Terrace, claimed to have been "once more overridden by ice" in northern area	Glacial T. 4 or 5.
Postglacial Terrace, followed by Younger Loess	Glacial T. 5 or 6.
Floodplain	Floodplain.

* The following details are necessary to show that certain ambiguities exist in the correlation of the terraces of the higher and lower course of the river. Readers not interested in these details may pass on to the summary, p. 60.

solid older formations form islands only in a thick cover of sandy Tertiary and Pleistocene sands and clays. In this area, especially between Weissenfels and Halle, Siegert and Weissermel studied the deposits of the Saale (1906, 1911), and obtained very important results concerning the connection of some of the terraces with deposits of the Scandinavian glaciations. The following table gives their terraces, and the equivalents in the middle course of the Saale (see bottom of p. 57).

The correlation of Siegert and Weissermel's terraces with those upstream is only in part based on measured heights above the floodplain, the chief link being provided by the conformable superposition of glacial deposits (*a*) on the 4th preglacial terrace of Siegert and Weissermel and on the Preglacial Terrace I of Toepfer, and (*b*) on the lower Main Terrace of Siegert and Weissermel and Toepfer's evidence that his Glacial Terrace 3 is the terrace immediately followed by the Penultimate Glaciation.

The Upper Main Terrace of Siegert and Weissermel, however, extended upstream into the Naumburg area by Naumann and Picard (1915), has been subdivided by Toepfer into his terraces 1 and 2 (the latter also comprising one or two points of Siegert's Lower Main Terrace (Siegert, 1909). Whether the Upper Main Terrace corresponds to Toepfer's Terrace 2, or to his Terrace 1, or to both these terraces, is difficult to decide on the evidence available. In any case it is certain that, whilst two terraces appear to intervene between the Antepenultimate and Penultimate Glaciations in the middle course of the river, downstream in the Halle area the same may, but need not be true.

A more serious difficulty is encountered in connection with Glacial Terrace 4. This terrace has, by Toepfer, been equated with Naumann and Picard's 2nd Interglacial Terrace in the area common to these investigators (Toepfer, 1933, p. 44). He was, of course, entitled to do so, since both he and Naumann and Picard considered precisely the same localities, but the question arises whether Naumann and Picard were right in identifying this terrace of the middle course with the terrace of the Halle area called 2nd Interglacial Terrace by Siegert and Weissermel. This assumed connection is an old one; it goes back to Siegert (1909), who connected the Köppelberg near Kösen (12 m. above floodplain) with the locality Salpeterhütte near Weissenfels (" few m. above floodplain ") over a distance of 18 km. This connection is open to criticism.

In the area of Toepfer, Naumann and Picard, two low terraces are observed (Terraces 5 and 6 of Toepfer, Postglacial Terraces *a* and *b* of Naumann and Picard) below Terrace 4, *i.e.* three terraces in all post-date the Penultimate Glaciation. The bench of Terrace 5 is about 4 m. above floodplain, that of Terrace 6 is below floodplain and its aggradation surface lies about 1–4 m. above floodplain. In Siegert and Weissermel's area, only two terraces post-dating the Penultimate Glaciation have so far been observed, namely *their* 2nd Interglacial Terrace (bench 2–3 m. above floodplain, surface 7 m. above floodplain), and their Postglacial Terrace (aggradation surface few metres above floodplain). In their position relative to the present floodplain these two terraces correspond to Toepfer's Terraces 5 and 6, so that the 2nd Interglacial Terrace of Siegert and Weissermel would correspond to Naumann and Picard's Postglacial Terrace α, whilst Naumann and Picard's 2nd Interglacial Terrace (= Toepfer's Glacial Terrace

4) would not exist (or not yet have been identified) in the Halle area. This is the view expressed in the table, Fig. 18.

The alternative is to follow the old interpretation that Terrace 4 is the same as Siegert and Weissermel's 2nd Interglacial Terrace near Halle. Support for this view is obtained if one plots the benches of the various terraces, and then considers the general gradient of Terrace 4 relative to the higher terraces and not its gradient relative to the present floodplain. In this case, only Terrace 5 or 6, but not both, would be identifiable in the Halle area.

On the available evidence it is impossible to decide which of the alternatives is correct.

? WARTHE GLACIAL DEPOSITS ON TERRACE 5.—A few miles downstream from Halle (*i.e.* north of Siegert and Weissermel's area) Wüst (1911) found glacifluvial gravel on a terrace the surface of which is only 6 m. above floodplain. A yet lower terrace is observed at 3·5 m. above floodplain.* Soergel (1924) correlated these two terraces with his Terraces 5 and 6. If Wüst is right, then the outwash of a glacial phase later than the Penultimate Glaciation would have reached to north of Halle, and this can only have been the Warthe phase.

? EXTENSION OF WARTHE PHASE SOUTH OF THE ELBE.—That the Warthe phase reached at one time considerably farther south than the Fläming moraine, its generally accepted southern limit, has been suggested repeatedly. Linstow (1906) found moraines and an *urstromtal* south of the Elbe, showing than an ice-margin lay only 20 km. north of Halle. Linstow was convinced by the morphological freshness of the moraines that this was an extreme stage of the Last Glaciation, but he did not attempt to disprove the alternative that it was a retreat stage of the Penultimate Glaciation.

Siegert and Weissermel (1911) firmly hold the view that the Last Glaciation reached the Halle area. As evidence, they claim that (*a*) on sheet Schraplau, 20 km. west of Halle, the terrace of the Weida river equivalent to the 2nd Interglacial Terrace of the Saale river was overridden by ice, (*b*) that esker-like hills of the Last Glaciation occur on sheets Dieskau and Landsberg, 5–10 km. east of Halle, and (*c*) that the interglacial of Rabutz, 13 km. east of Halle, is covered by a genuine boulder-clay of the Last Glaciation, and not by a solifluction horizon.

INTERGLACIAL OF RABUTZ.—By far the most important locality is Rabutz. A clay deposited in a buried vale about 200 m. wide and at least 750 m. long, containing abundant interglacial fauna and flora, and "Mousterian" implements, is undoubtedly of Last Interglacial age. It rests on the entire succession of boulder-clays and glacial basin-clays constituting the deposits of the Penultimate Glaciation, beneath which the Main Terrace, the Antepenultimate Glaciation (with boulder-clay and varved clay, resting on the youngest preglacial Saale gravels) have been identified in one and the same boring (Siegert in Siegert and Weissermel, 1911). The floral succession (Weber, 1917) leads from cold conditions up to mixed oak forest containing

* The three higher terraces observed by Wüst, the upper two of which are preserved in vestiges only, are later than the first glaciation of the area, as they contain erratic pebbles. Since Wüst's area is just below the porphyry bar which the Saale river had to cut through after the Penultimate Glaciation, these gravels may represent stages in the down-cutting of the gorge, and therefore not be comparable with the Saale terraces south of Halle. Wüst invoked tectonic movements to explain them.

hornbeam. The latest comprehensive description of Rabutz is by Soergel (1920).

All workers agree therefore that the Rabutz clay is of Last Interglacial age. The great question is whether the bed of clay with pebbles and stones which covers the interglacial deposit is a boulder-clay, or a solifluction deposit. Siegert, and Weissermel and Picard (1926, 1929), maintain that it is a boulder-clay since it contains erratics irregularly distributed and up to 0·5 m. diameter, and since the country is "as flat as a table," there being no opportunity for solifluction. Keilhack and Grahmann (1921, 1926) maintain that it is a gravelly loam, a solifluction deposit. Their arguments against boulder-clay nature of the deposit are (1) that it contains no lime, (2) that it is not sharply separated from the underlying interglacial clay. Both are considered as inconclusive by Weissermel and Picard (1929). These authors sum up the situation by stating that nobody would object to the boulder-clay nature of the deposit if it lay north of the Elbe, but the wish to restrict the Fläming phase to the north of the Elbe in conformity with the ruling opinion induces workers to regard it with suspicion. One must admit, however, that a boulder-clay in such a crucial position as at Rabutz requires more definite evidence as to its true nature than a boulder-clay of the Last Glaciation north of the Elbe. Milthers (1934) has shown that the counts of erratics carried out in boulder-clay of this area indicate a connection with the Fläming or Warthe Glaciation. This would substantially support Weissermel and Picard's view, were it known from which stratigraphical level Milthers's countings came.

One is, therefore, at present unable to form a clear opinion whether this covering stratum of Rabutz is a moraine or not. The possibility remains, however, and with it the possibility of a connection of Terrace 4 or 5 with the deposits of the Warthe phase.

Halle Area: Summary.—It has been necessary to discuss the Halle area in some detail in order to show that, whereas it completely confirms the correlation of Terrace 3 (Toepfer) with the Penultimate Glaciation, the identification of some of the other terraces is still left uncertain. A few essential facts have emerged, however, namely that—

(1) Between the advance of the Antepenultimate Glaciation and that of the Penultimate Glaciation into Thuringia *two* terraces were formed in Thuringia (Glacial Terraces 1 and 2), but only *one* has so far been found in this position in the Halle area.

(2) That after the Penultimate Glaciation, *three* terraces were apparently formed in Thuringia, but only *two* have been found in the Halle area.

It will be seen in the following paragraphs that this reduction in the number of Glacial Terraces is a characteristic of the Saxonian rivers also.

Other Rivers of the Elbe System.—Like Saale and Ilm, the Saxonian rivers, Elster and Mulde, belong to the area of the Elbe. They were studied by Grahmann (1925, 1928), and their correlation with the Ilm-Saale discussed by Toepfer (1933), Zeuner (1938) and Soergel (1939). Again we encounter the problem of correlating the two lowest terraces with the three lowest of the Ilm and middle Saale. Grahmann found two terraces only, but he regards the floodplain as deposited in a cold climate.

The Elbe in Saxony has been studied by Grahmann (1932, 1933). The complete sequence here is difficult to ascertain, since the river enters the

North German Lowlands, a zone of tectonic subsidence where younger deposits often completely veil the older ones.

Farther to the east, the Spree (a tributary of Havel-Elbe ; Neumann, 1934) shows the same rhythm as observed near Halle and in western Saxony, with one aggradation intervening between the Antepenultimate and Penultimate Glaciations, and two following the Penultimate Glaciation. The link of the third terrace with the urstromtal of the Warthe Phase (Fläming moraine) is of particular importance.

THE ODER SYSTEM.—Neumann (1934) also investigated the terraces of the Lusatian Neisse, which is a tributary of the Oder. He found the same succession as on the Spree.

In Silesia the river system of the Oder derives much of its water from the Sudeten Mountains. The only tributary which has up to the present been investigated in some detail is that of the Glatzer Neisse (Zeuner, 1928, 1938 ; Berger, 1931 ; Soergel, 1939). Its terrace system resembles those of the rivers farther west, and of Saxony in particular (Fig. 18). The section of Johnsbach, which contains a flora of early Pleistocene age, adds a further cool phase to the succession (Zeuner, 1929 ; Stark and Overbeck, 1932). This may be a phase preceding the Elster Glaciation.

In short, the river systems of the Elbe and of the Oder show similar successions of Pleistocene terraces. We have now to consider briefly the remaining two systems of central Europe, those of the Weser and of the Rhine, both west of the Elbe.

WESER SYSTEM.—The Weser (Siegert, 1921 ; Soergel, 1925 ; Grupe, 1926 ; Soergel, 1927 ; Zeuner, 1938 ; Soergel, 1939) with its ten or more terraces resembles the Ilm-Saale. Since the Weser, however, flows directly into the North Sea, it is liable to eustatic interference. Divergence of opinion between Soergel and Grupe may be due to this fact. The latest interpretation of the Weser system is given in Fig. 18.

RHINE.—One cannot expect that the terraces of the Rhine, a river at present over 700 miles long (and about 1100 miles long during the glacial phases while the sea-level was low), are uniform throughout its course. As far as Schaffhausen, between Lake Constance and Basle, the Rhine flows through areas which were glaciated during the Last Glaciation. Thence to beyond Basle, the terraces are determined by the retreat phases of the Last Glaciation (see p. 45). From Basle as far as Mayence the Rhine runs through the wide rift valley bordered by the Vosges and the Black Forest, where the ground has been subsiding so that the youngest gravel sheets cover nearly the entire valley. In the Rhenish Schiefergebirge, however, terraces are well developed (Mordziol, 1926). The most important zone is that between the Schiefergebirge and (and including) the Ruhr. Here the contact of the Scandinavian Saale Glaciation with the so-called Middle Terrace of Steinmann (1926 ; lower Middle Terrace of Breddin, 1928) could be established. The Main Terrace is clearly of the age of the Elster Glaciation ; it is subdivided into an upper and a lower Main Terrace by Breddin. A glance at the correlation table, Fig. 18, will show that a duplication of each of the four major glaciations is expressed by the terraces of the lower Rhine.

Beyond the Ruhr, however, the Rhine terraces were increasingly affected by the fluctuations of the sea-level (see also p. 238).

In 1939 Soergel undertook to compare with, and fit into, the system of Thuringian terraces those observed on the Rhine and its tributaries. He considers that four "middle terraces" are intercalated between the Main Terrace (of the Antepenultimate Glaciation) and the Low Terraces (of the Last Glaciation). Since the *fourth* Middle Terrace is, on the Ruhr, connected with the boulder-clay of the Penultimate Glaciation, three terraces are regarded as intercalated between this and the Antepenultimate Glaciation in the Rhine area, compared with two in Thuringia and one in Saxony. The distinction of four independent "middle" terraces requires further substantiation. It was based in the first instance on the basin of Neuwied, in the Rhenish Schiefergebirge, an area of tectonic movement and late Pleistocene, if not Postglacial, volcanic activity. Müller (1938), in a remarkable survey of the terraces of the Rhine and its tributaries, says that the

SILESIA	MULDE-ELSTER	ILM-SAALE	WERRA-WESER	RHINE	CONFORMABLY COVERED BY
	pls φ ?	PREGLACIAL T. IV	VII	a very high terrace	
	pls φ ?	PREGLACIAL T. III	VIII	a very high terrace	
	II (p2s φ)	PREGLACIAL T. II	IX	?upper part of MAIN TERRACE	
f(?g)	TERR.I	PREGLACIAL T. I	X	MAIN T.	ELSTER MORAINE
(e)	–	GLACIAL T. 1	IIa	–	
d	TERR.1	GLACIAL T. 2	IIb	HIGH TERRACE or UPPER MIDDLE T.	
c	TERR.2	GLACIAL T. 3	MAIN T.: IIc	LOWER MIDDLE T.	SAALE MORAINE
–	–	GLACIAL T. 4	I2	–	
b	d3	GLACIAL T. 5	Pa	LOW T.	YOUNGER LOESS I
a	da	GLACIAL T. 6	Pb	INSELTERRACE (LOWER LOW T.)	YOUNGER LOESS II
FLOOD-PLAIN	FLOOD-PLAIN	FLOODPLAIN (GLAC. T. 7?)	Pc	?	

Fig. 18.—Tentative correlation of the climatic aggradation terraces of some German rivers. After Zeuner (1938).

remains of the middle terraces are scanty, and that the correlation of the benches distinguished by various authors, especially on the Moselle with those on the Rhine, cannot be considered as settled. For this reason Steinmann's divisions (1926) combined with those of Breddin (1931), incomplete though they may prove to be, have been accepted in the present context.

On the whole, however, the agreement of the Rhine system with that of the Weser, Elbe and Oder is most remarkable. Compared with the standard area, Thuringia, the differences are limited to (*a*) the presence of a supernumerary terrace between the lowest Preglacial and the first Glacial Terrace (as suggested by Soergel), and (*b*) the absence of evidence for the fourth Glacial Terrace of Thuringia in the Rhine area (Soergel's terminology).

According to Breddin both Low Terraces are covered with conformable loess or loess-like deposits of the type of the Younger Loess (Soergel, 1939, p. 191.)

River Terraces of Central Europe: Summary.—The systems of terraces of the rivers of central Europe, which are removed from the

influence of the changing sea-level, thus resemble one another to a high degree. They reveal a most interesting sequences of cold phases (Fig. 18).

There were at least eight major phases of this kind, and one or several minor phases which are not recognizable everywhere. The eight major phases can be grouped in four pairs. Of these, the latest pair, linked with the Younger Loess (Rhine, Ilm-Saale, Glatzer Neisse), is the equivalent of the Last Glaciation. The higher of them is apparently connected with the Warthe Glaciation in Lusatia. Of the preceding pair, the lower terrace is linked with the morainic deposits of the Penultimate Glaciation (Saale Glaciation) of Scandinavia and North Germany (rivers Saale, Mulde, Spree, Lusatian Neisse, Glatzer Neisse, Weser, Ruhr). The higher terrace of this pair bears in many places a conformable Older Loess, as does the lower one in areas removed from the ice-margin.

The lower terrace of the third pair (counting from the present) is connected with morainic deposits of the Antepenultimate Glaciation in the areas of the Saale and its tributaries, and the Weser, and possibly the Glatzer Neisse. The higher terrace of this pair (upper Main Terrace of Rhine, Preglacial Terrace II of Thuringia) is unanimously regarded as an early phase of the lower, and therefore of the Antepenultimate Glaciation. The highest pair, Preglacial Terraces III and IV, is still cold in the character of its gravels, but it is not sharply differentiated from the still higher Preglacial Terraces, of which several have been found. These cannot be correlated with glacial phases in North Germany, but it must be remembered that the Early Glaciation of the Alps (Günz) was preceded by several glacial phases according to Eberl (see p. 43).

What are probably two minor phases are represented by the two additional terraces of the lower and upper Saale. As was said on p. 59, the view here tentatively adopted is that Soergel's First and Fourth Glacial Terraces are the supernumerary ones peculiar to this area. On neither of these has a conformable loess been definitely established, nor has either yielded a cold fauna. If they owe their origin to cold oscillations at all (which remains to be proved), they presumably represent minor phases, much weaker than, for instance, the Weichsel Phase.

Finally, the floodplain gravels have to be regarded as a terrace through which the modern river has not yet cut down. These gravels are considered by some authors, on the evidence advanced by Grahmann, to represent a third cold phase of the Last Glaciation, but since one of the Low Terraces is missing in Grahmann's area (as in many others), it is possible that such floodplain gravels are merely the equivalent of the lower Low Terrace, *i.e.* the second cold phase of the Last Glaciation, and do not represent a third phase. The possibility of a third, weak phase of the Last Glaciation must not, however, be overlooked.

c. THE LOESS BELT OF CENTRAL AND EAST EUROPE.

Subdivisions of the Loess.—Thus the terraces of the rivers afford a detailed relative chronology for the climatic oscillations which occurred during the Pleistocene in central Europe. If this chronology is to be of more than local value, in other words, if it does provide a suitable stratigraphical basis for subdividing the Pleistocene, one must expect to find

corroborative evidence in the non-fluviatile deposits as well, especially in the loess districts.

Climate of the Loess Belt.—The periglacial loess belt of Europe extended, with local interruptions, from north France and south England through central Europe to south Russia (Fig. 19). In this vast area the repeated changes from a humid and temperate climate to a dry and cold one, and *vice versa*, left their traces in a succession of weathering soils and beds of loess. It must be kept in mind, however, that the climate of so vast a region is not quite uniform and has never been so in the past.

At present the districts composing the loess belt are part of the northern

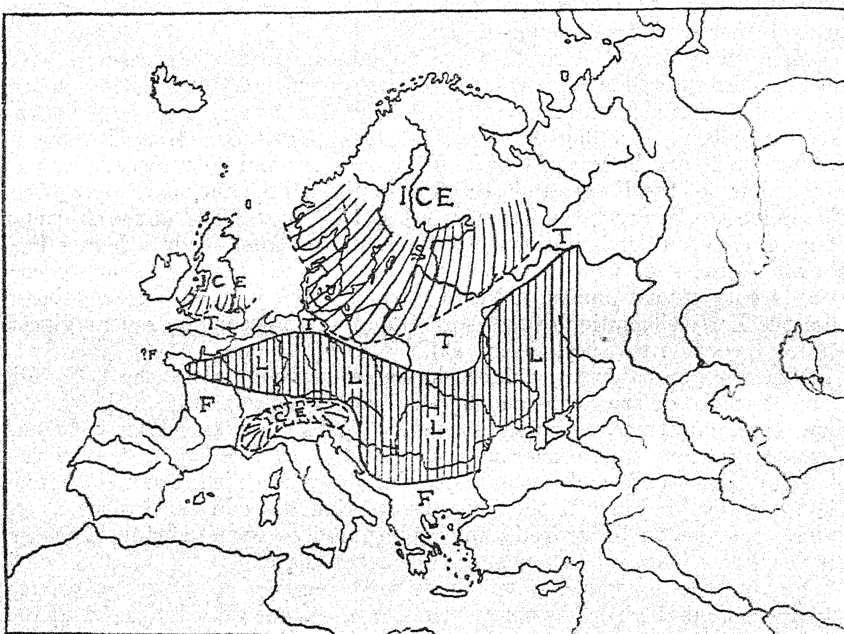


Fig. 19.—Approximate distribution of the climatic zones during a major glacial phase in Europe. Example: First phase of the Last Glaciation. T. Tundra belt. L. Loess belt. F. Temperate Forest, possibly linked with the tundra belt in the extreme west. The loess area was continuous in the east, but in the west it was interrupted by many districts without loess-sedimentation. In England, loess was deposited in many scattered areas in the south which have not yet been mapped and, therefore, not entered on the chart. After Zeuner (1937*a*).

temperate zone; yet north France and south England have mild winters and mild summers (London, for example, January average + 3·4° C., July + 17·3° C., annual mean + 9·8° C.), whilst south Russia has severe winters and hot summers (Kišinev, January − 3·5° C., July + 22·4° C., annual mean + 9·8° C.). The former type of climate is called *oceanic*, the latter *continental*, and the difference is due to several factors, chief among them the

moderating influence of the ocean, and the intensification of heating and cooling by radiation in inland areas.

Although the primary climatic changes which caused the Pleistocene ice-sheets to grow were not of a continental character (see p. 154), the continental type of climate was intensified as the ice-sheets grew, and it gradually extended into the central and western parts of Europe. Under its influence loess deposition began, and the loess belt also extended westwards.

It is evident that it depended on the intensity of the cold phase how far westwards the continental type of climate could spread. Accordingly, one cannot expect to find evidence of minor cold phases in west Europe or, *vice versa*, of minor humid-temperate phases in east Europe. In central Europe, however, both kinds of minor oscillations made themselves felt, and this is why the climatic succession of loesses (as well as of climatic river terraces) in unglaciated Germany is so exceptionally complete.

YOUNGER LOESS AND OLDER LOESS.—In south-west and parts of mid Germany the loess has for a long time been subdivided into a "younger" and an "older" complex. The *Younger Loess* looks fresh and is of a light yellow colour. The weathering soils on it and in it are comparatively little developed, and often contain humic matter staining them grey. The *Older Loess* is darker, yellowish brown, and often deeply weathered. The difference is not due to the greater age of the older loess, but to its more intense weathering; it was subjected to weathering (mostly of the brown-earth type) for a very long period before the Younger Loess was deposited on top, and the Younger Loess, in turn, has suffered less weathering since its own deposition than did the Older Loess in the interval between its own deposition and that of the Younger Loess. This fact affords an indication of the relative duration of interglacial and interstadial phases in comparison with the Postglacial.

The differences between Older and Younger Loess are so marked that they can often be diagnosed in exposures in which only one of the varieties occurs. Sections showing both varieties in superposition are so abundant in the region mentioned that it is not worth while to quote examples here.

From the climatic point of view a section with both Younger and Older Loess has to be interpreted as follows:

Top weathering: Postglacial humid-temperate climate (short period).

Younger Loess: Cold steppe climate (periglacial).

Weathering of Older Loess: Interglacial humid-temperate climate (long period).

Older Loess: Cold steppe climate (periglacial).

SUBDIVISIONS AND AGE OF YOUNGER LOESS.—For some considerable time it has been known, and emphasized especially by Soergel (1919), that a fossil soil is often found subdividing the Younger Loess into two phases, I and II. This soil is, as a rule, fairly thin; it cannot indicate a phase of so long and intense a weathering as that which followed the formation of the Older Loess. Nevertheless, it must not be neglected for this reason.

The Younger Loess, with its two phases, represents the latest period of cold steppe conditions and is, in Thuringia and elsewhere, associated with two river terraces post-dating the Saale Glaciation. The higher of these sometimes carries both younger loesses in superposition, but the lower

carries invariably an undivided sheet of Younger Loess, *i.e.* Younger Loess II only. Thus one is justified in identifying the two Younger Loesses with the two phases of the Last Glaciation which, apparently, are represented by the Glacial Terraces 5 and 6 of the Thuringian succession. No satisfactory evidence has yet been advanced, however, for Glacial Terrace 4 being covered conformably by a loess.

Younger Loess often rests unconformably on older moraines, but it is not found on the moraines of the Weichsel phase. A Younger Loess, however, occurs in certain districts on the moraines of the Warthe Phase, but nowhere have two Younger Loesses been found on the Warthe moraines. These conditions suggest that the two Younger Loesses are contemporary with the Warthe and Weichsel Phases respectively. It is quite certain that one Younger Loess is contemporary with Weichsel, but it is possible that the Warthe phase is earlier than the Younger Loess I.

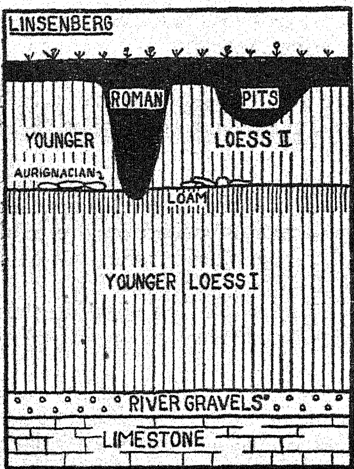


FIG. 20.

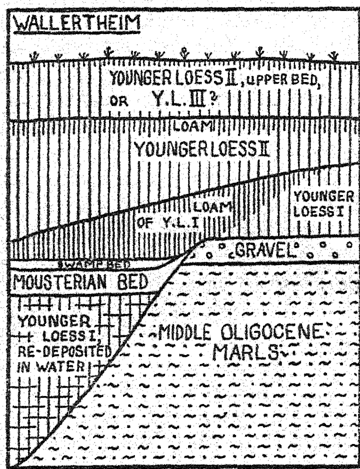


FIG. 21.

FIG. 20.—Section of the Linsenberg, near Mainz, Rhine Valley, with two younger loesses separated by weathering. After Schmidtgen (1930).

FIG. 21.—Section of Wallertheim, near Mainz, Rhine Valley, with three beds of Younger Loess separated by two weathering horizons. Based on Schmidtgen and Wagner, 1929.

SECTIONS ILLUSTRATING SUBDIVISIONS OF YOUNGER LOESS: LINSENBERG.—An interesting exposure of Younger Loess was described by Schmidtgen (1930; Neeb, 1924), from the Linsenberg near Mayence (Fig. 20). On the surface of the loamy soil formed on the Younger Loess I, an Aurignacian resting-place with remains of fauna was discovered. This stratum was covered by Younger Loess II. The accompanying bones, however, were perfectly fresh, and Schmidtgen concluded that no humid weathering took place after they had been deposited, and that this layer dates from the beginning of the cold phase evidenced by the Younger Loess II. It cannot belong to the preceding mild interstadial, during which the soil on the

younger loess I was formed, since in this case the bones would have been destroyed.

WALLERTHEIM, MOUSTERIAN.—Another important discovery is the site of Wallertheim, Rheinhessen (not far from Mayence) (Fig. 21). It was described by Schmidtgen and Wagner (1929). The authors found that, in the shallow valley of the Wiesbach, a Mousterian hunting site existed after the deposition of the main mass of the first Younger Loess. The stream had begun again to erode its valley, and a swampy patch served as a watering-place for the larger species of mammals. Loamified Younger Loess I, and fresh Younger Loess II, cover the site. The layer containing the fossils, therefore, although later than the main mass of the first Younger Loess, is earlier than the phase of loamy weathering which preceded the formation of the second Younger Loess; in other words, it was formed towards the end of the cold phase of Younger Loess I, still under comparatively cold conditions. This geological conclusion is confirmed by the fauna, which consists chiefly of animals of the loess steppe (*Alopex lagopus*, *Elephas primigenius*, *Arctomys* sp., *Bison priscus*, *Equus przewalskii*, *Rangifer tarandus*, *Tichorhinus antiquitatis*). Forms which indicate the presence of woods, however, had already appeared (*Bison* cf. *bonasus*, *Cervus elaphus*, *Sus scrofa*).

The Younger Loess II of Wallertheim is subdivided by a thin band of loam (less than an inch thick). Schmidtgen and Wagner interpret this as a mild oscillation of short duration. It is an interesting feature in view of the fact that the existence of a third Younger Loess has been suspected at a few other localities.

EHRINGSDORF, NEAR WEIMAR.—The famous Mousterian site of Ehringsdorf, near Weimar (Fig. 22), has yielded fossil remains of *Homo neanderthalensis* beside a very rich interglacial fauna and flora. Occupation layers and fossils occur in deposits of calcareous tufa, or travertine, formed by springs and resting on a glacial aggradation terrace of the river Ilm. According to Soergel (1926*a*, *b*) the succession is as follows:

H. Younger Loess II: Second cold phase of Last Glaciation.

G. Upper Travertine with cool-continental to temperate fauna (see p. 267): interstadial.

F. Younger Loess I, impregnated with calcium carbonate from above during the following milder phase: First cold phase of Last Glaciation. Called "Pariser."

E. Lower Travertine with temperate forest flora (ash, hazel, lime, oaks (*Quercus sessiliflora* and *mammuti*), ivy, *Thuja occidentalis*, walnut), mammals (see p. 265), *H. neanderthalensis*: decidedly warm interglacial or interstadial.

D. Floodloam with mammoth and European pond tortoise (*Emys orbicularis*): continental phase, cool, but not arctic.

C. River gravels of the Fourth Glacial Terrace with mammoth and woolly rhinoceros: cool phase.

(B. Period of erosion: interglacial or interstadial.)

(A. Third Glacial Terrace and Saale moraine: Penultimate Glaciation. Not at Ehringsdorf.)

This is one of the most important upper Pleistocene sections since, if Soergel's interpretation is correct, the presence of the two Younger Loesses and the superposition of the entire complex of loess and travertine on the

Fourth Glacial Terrace, the first terrace formed after the Saale Glaciation, fix its chronological position. The terrace is earlier than the Younger Loess I as well as (according to Soergel) the corresponding Fifth Glacial Terrace. It represents a comparatively slight period of aggradation with a moderately cool and continental climate, as evidenced by the presence of the pond tortoise (*Emys orbicularis* now goes as far north as Leningrad), together with the mammoth. This minor cool phase is very remarkable, as it appears to divide the Last Interglacial into an earlier and a later part. It reminds one of the Danish Middle Bed (p. 35), and of the intra-Monastirian oscillation of the sea-level.

The Lower Travertine in which the human bones were found was deposited under very mild climatic conditions. The fauna is that of a forest, and steppe and tundra forms are entirely absent. The flora comprises walnut and *Thuja*, suggesting that the annual mean was somewhat higher than at present.

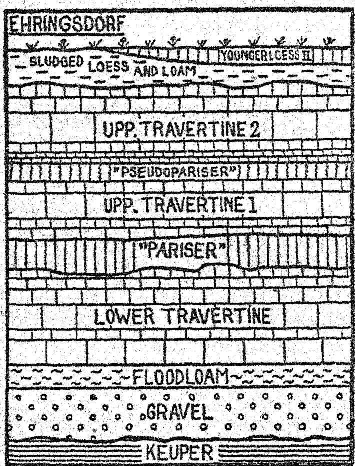


FIG. 22.

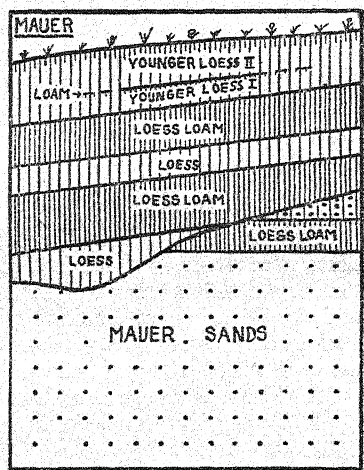


FIG. 23.

FIG. 22.—Section of the travertines and loesses of Ehringsdorf, near Weimar, Thuringia. Based on Soergel (1926*a*).

FIG. 23.—Loess section of Mauer near Heidelberg, Neckar valley, west Germany. North Wall of the section, which does not show the subdivisions of the fluviatile series but contains the entire loess succession. After Soergel (1928).

The Upper Travertine testifies to a recurrence of a more humid climate between the two Younger Loesses, but its fauna contains certain continental and cool elements beside species of the temperate forest. This shows that the climate was not fully interglacial, but rather interstadial.

Thus, if one follows Soergel, Ehringsdorf provides evidence for the post-Saale age of the Younger Loesses, for the interstadial character of the mild phase separating the two Younger Loesses, for the warm character of the phase which preceded the first Younger Loess, and for the presence of a post-Saale, but pre-Last Glaciation, oscillation with a cool-continental climate, evidenced by the Fourth Glacial Terrace.

The Last Interglacial would be represented by (*a*) the erosional phase between the Glacial Terraces 3 and 4, and (*b*), after the cool oscillation which caused the aggradation of the Fourth Glacial Terrace, the Lower Travertine. This subdivision is of considerable significance, as it is corroborated by the Danish Middle Bed and the intra-Monasterian oscillation of the sea-level; it will be discussed later on.

SUBDIVISIONS OF THE OLDER LOESS.—The Older Loess, which in many localities underlies the Younger Loess, can often be subdivided also. The Older Loess invariably antedates the Last Interglacial, and since the latter was a period of weathering and denudation several times longer than the entire Postglacial, it is not surprising that good sections in which subdivisions are preserved are much less frequent in the Older than in the Younger Loess.

In the catchment area of the Rhine at least three Older Loesses have been distinguished, separated from one another by loamy weathering horizons. Two outstanding sections showing them are those of Achenheim and of Mauer.

ACHENHEIM.—Achenheim lies at the foot of the Vosges, in Alsace, not far from Strasbourg, where thick strata of loess smooth out the transition from the mountain slopes to a terrace of the Rhine, on which the section rests. Charles Lyell had already been attracted by the loess of this area, but it was not until 1882 that divisions were established by Schumacher. Apart from the valuable work of this author, numerous investigators have contributed to the study of Achenheim, notably Andreae, Briquet, Forrer, Freudenberg, Gignoux, Koken, R. R. Schmidt, Wenz, Wernert, and van Wervecke. Recently, Wernert has published some of his most important observations, carried on for many years, and it is chiefly on his publications that I rely in the description that follows. All the important papers bearing on Achenheim are quoted in his paper (1929), which is easily accessible.

The section, from top to bottom, and its characteristic faunal contents, are as follows (faunas of weathering horizons are omitted in view of their uncertain origin):

K. *Recent soil.*—Age: Postglacial.

J. *Younger Loess II.*—Reindeer, horse, spermophile: cold steppe. Age: second cold phase of the Last Glaciation.

I. *Weak weathering soil.*—Age: interstadial.

H. *Younger Loess I.*—Horse, spermophile, mammoth, reindeer: cold steppe. Age: first cold phase of the Last Glaciation.

G. *Weathering loam, decalcified, partly sludged.*—Minimum age: soil of the Last Interglacial.

F. *Upper Older Loess.*—Solifluction at the base. Horse, reindeer, spermophile, marmot: cold steppe. Minimum age: Penultimate Glaciation, probably its second phase, since the middle Older Loess appears to represent its first phase.

E. *Weathering loam, slightly decalcified surface of middle Older Loess.*—The slight decalcification seems to indicate that this mild phase was an interstadial and not a full interglacial.

D. *Middle Older Loess.*—The middle Older Loess of Achenheim differs from typical loess in several respects. At the base ("loess atypique") it contains a forest fauna with *Elephas antiquus*, *Dicerorhinus merckii*, red

deer, roe deer, Irish deer, wild boar, large horse (*E. germanicus*), *Bos primigenius*, though the marmot occurs also.

A humose bed in the loess contained *Dicerorhinus merckii*, *Equus germanicus*, *Bos*, and abundant red deer.

Another "atypical" portion of the middle Older Loess, called "humose loess-loam" by Schumacher, has a hygrophilous forest fauna of mollusca, associated with *Dicerorhinus merckii*, abundant red deer, roe deer, but also the marmot.

It is apparent from the nature of this deposit, which is often humose or loamy, and from its largely humid and temperate fauna, that the conditions of formation cannot have been those of the periglacial steppe. It cannot be decided at present whether the middle Older Loess of Achenheim is a "secondary loess" re-deposited by hillwash in an interglacial climate (possibly in connection with tectonic disturbances, Wernert, 1936), or whether it is the marginal facies of an ordinary loess steppe which, in the climatically favoured Rhine valley, was bordered by forests along the mountains (Zeuner, 1937*a*, p. 392). The presence of the marmot supports the latter view. In any case, however, the middle Older Loess does not appear to represent a cold phase of great intensity. According to its stratigraphical position, it may represent a first phase of the Penultimate Glaciation (see below).

C. *Weathering loam, humous, formed on the lower Older Loess.* Age: interglacial.

B_2. *Fresh lower Older Loess.*—No fossils found. Age: Antepenultimate Glaciation, probably its second phase (compare A).

B_1. *Sand-loess and fluviatile sands from the Vosges.*—Solifluction observed. Mollusca of a cold climate, reindeer: cold phase. Age: probably early part of same phase as B_2.

A. *Marls and fluviatile sands of the Rhine.*—Mollusca of a temperate climate, *Hippopotamus*, *Alces latifrons*, *Dicerorhinus etruscus*: temperate climate.

The fauna of these sands recalls that of Mosbach near Mayence, as was suggested by Andreae in 1884 and confirmed by Wernert (1929), and also of Mauer near Heidelberg (see below). This palaeontological correlation is important, since the age of these localities has been determined independently as either the Antepenultimate Interglacial, or the interstadial preceding the second (main) phase of the Antepenultimate Glaciation. In this way, the *maximum* age of the loess section of Achenheim is fixed, and the two Younger Loesses and the upper and lower Older Loesses cannot but represent the two main phases of the Last Glaciation, the Penultimate Glaciation and the Antepenultimate Glaciation respectively. For the aberrant middle Older Loess there remains the interval between the Penultimate and Antepenultimate Glaciations, *i.e.* the Great Interglacial or, as suggested by its being enclosed by two weathering horizons, a cool phase ante-dating the Penultimate Glaciation. If so, it would agree with evidence obtained elsewhere that there was a first cold phase of the Penultimate Glaciation.

MAUER NEAR HEIDELBERG.—The section of Mauer near Heidelberg is famous for the discovery of the jaw of *Homo heidelbergensis*. It is situated in the bow of an abandoned meander of the river Neckar. A considerable thickness of fluviatile sands, the Mauer Sands, was deposited here shortly

before the river cut through the neck of the meander, thus laying it dry. In later phases of the Pleistocene, the Mauer sands were covered by a succession of beds of loess.

In addition to the jaw of *Homo heidelbergensis*, a rich mammalian fauna has been recovered from the Mauer Sands, characterized by *Trogontherium cuvieri* (a large beaver), *Arvicola greeni* (a water-vole), *Elephas antiquus* and *trogontherii*, *Equus mosbachensis*, *Dicerorhinus etruscus*, *Hippopotamus major*, *Alces latifrons*, *Machairodus* sp. This fauna (summaries, Rüger, 1931; Zeuner, 1937*b*) is characteristic of the time just preceding the Antepenultimate Glaciation. It is unlikely to be later in view of the presence of *Machairodus*, *Hippopotamus*,* *Dicerorhinus etruscus*, and others, and unlikely to be earlier than the Early Glaciation (Günz) in view of the presence of *Elephas antiquus* and other typically Pleistocene species. The fauna being of a forest type, its age, on *purely palæontological grounds*, is the Antepenultimate Interglacial in the widest sense. A more detailed comparison with the faunas of Mosbach, Süssenborn and the Cromer Forest Bed (Zeuner, 1937*b*) has shown that within that period of time, the Mauer fauna is likely to be comparatively late.

It is now interesting to see how the stratigraphical evidence compares with the faunal dating. Here is the succession (Fig. 23):

Bed, and climatic character.	Chronological interpretation (minimum age).
N. Recent soil: temperate . . .	Postglacial.
M. Younger Loess II: cold phase . .	LGl, second phase.
L. Weathering loam: temperate . .	interstadial LGl_1/LGl_2.
K. Younger Loess I (only in the north wall): cold phase . . .	LGl, first phase.
J. Weathering loam: temperate . .	Last Interglacial.
I. Upper Older Loess: cold phase . .	PGl, second phase.
H. Weathering loam: temperate . .	interstadial PGl_1/PGl_2.
G. Fresh middle Older Loess: cold phase	PGl, first phase.
F. Weathered fluviatile sands, and lower Older Loess, completely weathered, loamy. Weathering: temperate phase of long duration . .	Penultimate Interglacial.
(Deposition of lower Older Loess), and E. Fluviatile sands subjected to solifluction. Solifluction and deposition of loess: cold phase . .	ApGl, second phase.
– (Gap, produced by denudation) . .	Antepenultimate Interglacial, or interstadial $ApGl_1/ApGl_2$
D. Weathering horizon	
C. Floodloam	
B. Sandy calcareous floodloam . .	
A. Mauer Sands. A–D, including gap: temperate	

The strata covering the Mauer Sands were investigated by Soergel (1928, 1933), who also determined their minimum ages according to the detailed chronology based on the river terraces.

* In the Rhine area, *Hippopotamus* did not survive the Elster Glaciation.

The relative ages of the various loesses are evident. There are two Younger and three Older Loesses. The Mauer Sands, having been laid down in a temperate climate, must be earlier than the main phase of the Antepenultimate Glaciation, since they are covered by two pairs of loesses, separated by a prolonged period of weathering from yet earlier deposits of a cold phase which cannot but represent the Antepenultimate Glaciation. In the Alps this glaciation is composed of two phases separated by an interstadial (p. 43). Since Mauer shows only one loess antedating the Penultimate Interglacial, the interstadial between $ApGl_1$ and $ApGl_2$ would be the *latest possible* phase in which the Mauer Sands can have been laid down. If one does not accept the subdivisions of the glaciations evidenced by morainic, fluviatile and loessic deposits, the Mauer Sands would have to be relegated to pre-Pleistocene times, contrary to the evidence afforded by the fauna. If one accepts them, geological and faunal dating of the Mauer Sands agree most satisfactorily.

The minimum age of $ApGl_1/ApGl_2$ was suggested for Mauer by Soergel in 1928. In 1933, however, he attached greater significance to the gap above the weathered floodloam, C + D. The weathering, he claimed, took place *after* the denudation creating the gap, and it, therefore, must be assigned at least to the interstadial $ApGl_1/ApGl_2$. He supposed that the preceding erosion and denudation removed the periglacial aggradation formed during the first cold phase of the Antepenultimate Glaciation. On the strength of this argument the Mauer Sands would be at least of the age of the Antepenultimate Interglacial, *i.e.* preceding even the first phase of the Antepenultimate Glaciation.

Soergel's conclusion has certain advantages, but it also raises difficulties: The denudation may, after all, have been *contemporary* with the weathering, and the weathering may have occurred in the latter part of the same mild phase in which the Mauer Sands were laid down. This view (Soergel's of 1928) is supported by the palaeontological evidence, especially since Heller's work (1936) on the rodents proved Mauer to be later than the Cromer Forest Bed (see p. 105).

Travertine Sections of Cannstatt.—A succession of loesses similar to that of Mauer, but with an intercalation of a group of travertines assignable to the Great Interglacial, has been found at Cannstatt, near Stuttgart. The fact that the Cannstatt travertines are rather older than those of Ehringsdorf was established long ago. They are covered by the two Younger Loesses *and* by Older Loess (Bräuhäuser, 1909, 1916). Soergel (1929) found that there are two Older and two Younger Loesses overlying the upper travertine which, therefore, must be earlier than the Penultimate Glaciation.

The fauna, on the other hand, which is interglacial in character (with red deer, *Elephas antiquus*, brown bear) is phylogenetically later than that of Mauer, and loess material, incorporated in sludge beds to be mentioned presently, proves that a loess existed *before* the formation of the travertine began. This can only be the lower Older Loess of Mauer. Since the Mauer Sands antedate the second phase of the Antepenultimate Glaciation, the Cannstatt travertines must postdate it, *i.e.* they belong to the Penultimate, or Great Interglacial.

The main reason why Cannstatt is mentioned in this context is that

Soergel claims that the formation of travertine was twice interrupted. The springs ceased to flow during these intervals, and solifluction beds covered the slopes. Soergel regards this as evidence of two minor cool oscillations. The later of the oscillations would have been considerably shorter than the first.

It will be remembered that the First Glacial Terrace of Thuringia also indicates a cool oscillation during the Penultimate Interglacial.

LOESS OF THE WESER AREA.—Subdivisions of the Older Loess are not confined to the Rhine area. In the catchment area of the Weser, for instance, Selzer (1936) found the following succession (see table, p. 74).

Selzer's climatic interpretation of the sequence is based on the weathering of the various beds of loesses, and his correlation with the north German glaciations is supported by the fact that the entire succession rests on the "Middle Terrace," which was formed in an early phase of the Saale Glaciation. His sections thus confirm that the two higher Older Loesses represent two phases of the Penultimate Glaciation.

GERMAN LOESS; SUMMARY.—The instances given have shown that, in west and central Germany, the loess has to be subdivided into several phases, each of a more or less dry and nearly always cold climate (Exception: middle Older Loess of Achenheim, possibly owing to its abnormally favourable position), and separated by weathering loams, *i.e.* soils formed during mild and humid intervals.

The two Younger Loesses are definitely later than the Saale Glaciation. Both in north Germany and in the forelands of the Alps they occur almost entirely outside the moraines of the Last Glaciation. It is safe, therefore, to assume that they are contemporary with this glaciation. Just as there are two periglacial river terraces corresponding to the Last Glaciation, so there are two Younger Loesses. In some sections (Wallertheim for instance) the Younger Loess II is again subdivided by a thin band of weathering loam, suggesting a further mild oscillation and a division of the Last Glaciation into three phases instead of two. It has been supposed that the Pomeranian phase is responsible for this "third" Younger Loess. The mild interstadial separating it from the main part of the Younger Loess II would have been very slight.

The Last Interglacial is represented by a horizon of intense weathering on the Older Loesses, which indicates that the duration of this interglacial was considerably longer than that of the interstadial between the two phases of the Last Glaciation.

There are at least three Older Loesses. The uppermost precedes the Last Interglacial and, therefore, is likely to correspond to the Penultimate Glaciation. The middle Older Loess shows signs of having been formed during a cold phase of less intensity; it probably represents the first phase of the Penultimate Glaciation. If this is correct, the lower Older Loess would be the equivalent of the Antepenultimate Glaciation. Faunal evidence contained in underlying deposits is in good accord with this climatic correlation.

Loess of the age of the Early Glaciation (Alpine Günz) is not known with certainty.

These subdivisions are of more than local significance, since they apply to the whole of the periglacial area of Germany and, in addition, to other

Geological divisions.		Geological process.	Climate and type of weathering.
Last Glaciation of north Germany	2nd advance	Formation of Younger Loess II	Dry, cold (ice-wedges), mechanical weathering.
	Main fluctuation	Loamy weathering and denudation	Very damp, warm, intensive chemical weathering.
	1st advance	Formation of Younger Loess I Aggradation of the Low Terrace	Dry, cold (ice-wedges), mechanical weathering.
Last Interglacial		Intense loamy weathering, partly formation of swamps, valley erosion	Warm, very damp, intense chemical weathering.
Penultimate Glaciation of north Germany	2nd advance	Formation of Older Loess II	Dry, cold (ice-wedges), mechanical weathering.
	Retreat phase	Loamy weathering and denudation	Warm, damp, chemical weathering.
	1st advance	Formation of Older Loess I Aggradation of the Middle Terrace	Dry, cold.
Penultimate Interglacial		Valley erosion	

parts of the periglacial area as far east as south Russia and as far west as France and England. The French and British loesses will be discussed separately later on, but two districts of eastern Europe may help here to illustrate that the detailed chronology applies to the entire loess region of Europe.

HUNGARIAN LOESS.—In Hungary, little attention was paid to the subdivisions of the loess until E. Scherf, with the support of the Hungarian Geological Survey, began to study in detail the thick deposits of the Hungarian Lowlands. He used pedological methods for his work, so that his results regarding the existence of weathering horizons in the Hungarian loess may be considered as very reliable. In 1936 Scherf reported to the meeting of the International Association for the Study of the Quaternary Period in Vienna his important discovery of a large number of weathering horizons in the loess at Paks, 30 kilometres south of Budapest.

The pit of the brickyard at Paks is as much as 143 ft. deep. Scherf found eleven weathering horizons which he is inclined to correlate with the various interglacials and interstadials of the detailed chronology down to an interstadial separating two phases of the Early Glaciation. The bottom loess, resting on Pannonian Sand (Pliocene), is regarded as that of the first phase of the Early Glaciation, and the minor phases (which are not represented by loesses even in central Germany) are supposed to be represented by loesses also. It is possible that, in the Hungarian Plains, which are very susceptible to slight climatic changes, the minor phases should have produced loessic deposits. On the other hand, an alternative explanation is offered by Eberl's pre-Günzian phases (p. 43), which might be represented by three to five loesses in addition to the eight loesses which might have been formed since the first phase of the Early Glaciation. The correlation of the Hungarian loesses with other districts thus remains a problem, but it is a fact that their number far exceeds four. It is to be hoped that Scherf's final publication on the subject will supply the evidence required for the correlation of the individual phases with those of central Europe.

UKRAINE.—By far the largest loess area of Europe is that of south Russia. Here, in the Ukraine, Krokos (1927, 1935) found up to six beds of loesses, separated by well-developed soils, mostly of the chernozem type (p. 15). Of these loesses, the third counted from the top is contemporary with the Saale Glaciation, which penetrated into the loess and left a sheet of ground-moraine there. Accordingly, Krokos considered the two upper loesses as equivalents of two phases of the Last Glaciation. The section of Sbranki, near Ovruča, north-western Ukraine, is a good example (Krokos, 1930):

A. 0·40 m.: Recent soil, partly denuded.
B. 2·50 m.: Yellow loess.
C. 0·45 m.: Grey humous loam with tubules of $CaCO_3$.
D. 2·00 m.: Yellow loess.
E. 1·79 m.: Grey forest soil, developed by degradation on an original chernozem.
F. 3·40 m.: Yellow loess-like loam with tubular concretions of $CaCO_3$.
G. >1·46 m.: Reddish-brown, sandy boulder-clay.

The soil (C) which separates the two Younger Loesses is much thinner than the soil which developed on the Older Loess (E), just as in central

Europe. The most remarkable feature of the Ukrainian succession is the moraine (G) of the Dnjepr lobe of the Saale Glaciation, which penetrated into the loess area while the upper Older Loess was forming. Such a penetration of the ice into the contemporary loess belt has not been observed elsewhere. It appears to have been caused by a temporary extreme advance* of the ice under intensely continental conditions.

Below the upper Older Loess containing the Dnjepr moraine, three further loesses, separated by weathering soils, have been established. Their correlation with the lower Older Loesses of central Europe is a matter of conjecture and need not be discussed here (summary of views, Zeuner, 1938); it suffices to note that the total number of loesses in the Ukraine is at least six.

EAST EUROPE: SUMMARY.—The divisions of the loess of east Europe thus appear to be essentially the same as those of central Europe, and the summary given for the latter on p. 73 applies to the former in almost every respect. Only the number of Older Loesses is larger in the east (four in the Ukraine, six or more in Hungary), but some of these may yet be discovered in central Europe.

D. CAVE AND SOLIFLUCTION DEPOSITS.

PETERSFELS; SOLIFLUCTION.—Solifluction beds are frequent in the Pleistocene of central Europe, though the phenomenon as such appears to have attained its fullest development in west Europe. As an instance of a section composed chiefly of solifluction material, in front of a cave, the Petersfels near Engen, in the vicinity of Lake Constance, may be mentioned. It was excavated by Peters (1930).

The section of the detrital cone in front of the cave is made up, from top to bottom, of:

F. Weathering loam, 15 cm.
E. Coombe rock of local Jurassic limestone, 40 cm.
D. Sludge with Magdalenian, 50 cm.
C. Earth with Magdalenian *in situ*, 20–40 cm.
B. Weathering loam, 15–20 cm.
A. Coombe rock of local Jurassic limestone, 1 or more m.

The age of the deposits was determined by Toepfer (in Peters and Toepfer, 1932). The top soil, F, is Post-glacial and Recent. The two coombe rocks, A and E, of which the upper is much weaker, must correspond to two phases of cold climate with permanently frozen subsoil. Since the site lies in a glacifluvial valley issuing from the outermost terminal moraine of the last Alpine glaciation, the lower coombe rock can at the earliest belong to this phase (Schaffhausen Phase), or perhaps the following (Diessenhofen Phase). The upper coombe rock must represent a later phase, separated from the former by a distinct oscillation with milder conditions. This is likely to have been the Stein Phase (p. 48). The Magdalenian deposits with their reindeer fauna date from the time of deterioration of climate at the beginning

* Eberl, too, has observed a maximum advance of the Riss glaciers beyond the terminal moraines of this glaciation.

of this later cold phase. This evidence supports the conception that a mild interstadial separates the Stein Phase of the Rhine glacier from the earlier phases of the Last Glaciation.

E. CLIMATIC FLUCTUATIONS OF CENTRAL AND EAST EUROPE: SUMMARY.

PENULTIMATE GLACIATION.—The pivot of the relative chronology of the Pleistocene of central and east Europe is the Saale Glaciation. Its ice penetrated far into the zone which, during the majority of the cold phases, constituted the periglacial belt, and its interference with periglacial deposits has furnished a most valuable clue for the correlation of otherwise unconnected deposits. The Saale moraine has been linked chronologically with the Third Glacial river terrace as well as with the upper Older Loess.

ANTEPENULTIMATE GLACIATION.—For the climatic phases preceding the Saale Glaciation, the moraine of the Elster Glaciation is of considerable importance. It is connected with the "First Preglacial" river terrace, and it is highly probable that the German lower Older Loess corresponds to it.

PENULTIMATE INTERGLACIAL.—The time between these two great Scandinavian glaciations comprises more than a simple interglacial. Two aggradation terraces were formed in this interval; the *later* of these ("second Glacial Terrace") has been found in most districts and is linked with an Older Loess* (the "middle Older Loess"), whilst the earlier ("First Glacial" Terrace) is more local and of minor importance. The weathering of the lower Older Loess (of Elster age) was intense, indicating a long period of humid and temperate climate, whilst the middle Older Loess is in some sections less deeply weathered, so that the mild period immediately preceding the formation of the upper Older Loess (of Saale age) appears to have been shorter and (or) less intense. For this and other reasons given in this chapter, the middle Older loess and the second Glacial Terrace appear to be closer to the Saale Glaciation than to the Elster Glaciation, and it is permissible to regard the cold phase, during which they were formed, as the first phase of the Saale Glaciation *sensu latiori*.

The space of time between the Elster Glaciation and the first phase of the Saale Glaciation (*i.e* the Penultimate or Great Interglacial) was of long duration, as evidenced by the intensity of weathering, denudation and erosion. The First Glacial Terrace, however, subdivides it, indicating that the climate approached glacial conditions for a while. The fauna of this terrace, however, comprises, according to Soergel, forest forms only, and the climate cannot have been very cold. The First Glacial Terrace, therefore, appears to bear evidence of a minor cool-continental oscillation subdividing the Penultimate Interglacial. Two cool phases interrupted the formation of travertine at Cannstatt during this interglacial, according to Soergel.

PRE-ELSTER COLD PHASES.—Several cold phases preceded the Elster or Antepenultimate Glaciation. Toepfer found as many as six. Since there is no definite morainic evidence in north Germany of glacial phases earlier than Elster (although they have been suspected), a safe correlation is not

* According to Toepfer (1933), the floodloam of the Second Glacial Terrace of the Saale river passes into an Older Loess.

yet possible. It is most remarkable that in the Alps, where the phase Mindel 2 is regarded as the equivalent of Elster, Eberl found evidence of seven glacial phases preceding Mindel 2, namely Mindel 1, Günz 2, Günz 1, the three Donau phases, and the Staufenberg gravels. One is tempted to correlate these Alpine phases (except the Staufenberg gravels) with the higher preglacial terraces of the periglacial zone.

Last Glaciation.—Returning once more to the Saale Glaciation, the "pivot" of our chronology, it is known to have been followed by several climatic phases.

The period which has elapsed since the end of the Saale Glaciation comprises the Last Interglacial, the Last Glaciation with its phases, and the Postglacial. Two phases of the Last Glaciation are easily recognized in the periglacial area, since there are almost everywhere two Younger Loesses, coupled with two aggradation terraces. The ice of the Last Glaciation, however, did not reach the districts where the aggradation terraces formed, and the only means of correlating morainic phases of the Last Glaciation with periglacial phases is afforded by the second Younger Loess, which nowhere covers the moraines of the Weichsel Phase, and keeps some distance away from them. It is probable, therefore, that Weichsel was contemporary with the Younger Loess II.

Since the Younger Loess II appears to correspond to Weichsel, the Younger Loess I might be contemporary with the Warthe Phase, but definite evidence is wanting.

Another problem is that of the Pomeranian Phase. It being separated from Weichsel by a decidedly cold interstadial, one might be inclined to correlate with it the rare traces of a third Younger Loess and of solifluction deposits, separated by a weak weathering horizon from the second Younger Loess or equivalent deposits (Wallertheim, Petersfels, for instance), but whether such correlation is justified remains to be seen.

Last Interglacial.—The mild period that intervened between the second (main) Saale Phase = Third Glacial Terrace = upper Older Loess, and the formation of the first Younger Loess, is called the Last Interglacial. During this period chemical weathering was intense, indicating long duration and (or) great intensity, as in the Penultimate Interglacial.

Some observations which make it possible to define more precisely the climatic character of the Last Interglacial and which could not find a place in the survey of the districts above may be added here.

From the Rhine to Poland, the buried soils of the Last Interglacial are nearly everywhere of the brown-earth type. In the Ukraine, black-earth (chernozem) is dominant. This distribution of temperate forest soil and temperate steppe soil agrees very closely with that of the present day. Moreover, the islands of chernozem found nowadays in dry localities of central Europe were steppe islands with chernozem in the Last Interglacial also (Figs. 6 and 7). The Postglacial chernozem of these small and isolated areas is now in a state of soil-degradation ; it was formed during the Boreal (Zeuner, 1929), under a climate somewhat more continental than that of the Atlantic and Subatlantic phases, and is now being degraded, a brown-earth or even a podsol profile developing on it under more humid conditions. For some time during the Last Interglacial, therefore, the climate of central Europe was more continental than at present, with hotter and drier summers.

This is confirmed by another interesting observation. From southwest Germany westwards, in France particularly (and also in the Thames valley), the soil of the Last Interglacial has a colour more reddish than that of ordinary brown-earth* and reminiscent of the Mediterranean variety of this

PHASE	RIVER TERRACES (CLIMATIC)	GERMAN LOESS	UKRAINIAN LOESS	NORTH GERMAN MORAINES	CLIMATIC CHRONOLOGY	FAUNA
LATE GLACIAL & POSTGLACIAL						
LGl3		?YOUNGER LOESS III		POMERANIAN	LAST GLACIATION PHASE 3	E. PRIMIGENIUS RANGIFER
						RANGIFER C. ELAPHUS
LGl 2	GLACIAL TERR. 6	YOUNGER LOESS II	BUG LOESS	WEICHSEL MAIN PHASE	LAST GLACIATION PHASE 2	E. PRIMIGENIUS RANGIFER
						E. PRIMIGENIUS C. ELAPHUS
LGl 1	GLACIAL TERR. 5	YOUNGER LOESS I	UDAJ LOESS	?WARTHE PHASE	LAST GLACIATION PHASE 1	E. PRIMIGENIUS RANGIFER
L IGl					LAST INTERGLACIAL	E. ANTIQUUS C. ELAPHUS
	GLACIAL TERR. 4			DAN. MIDDLE BED	COOL OSCILLAT'N	E. PRIMIGENIUS
						E. ANTIQUUS C. ELAPHUS
PGl 2	GLACIAL TERR. 3	UPPER OLDER LOESS	DNJEPR LOESS	SAALE	PENULTIMATE GLACIATION, PH. 2	E. TROGONTHERII RANGIFER
PGl 1	GLACIAL TERR. 2	MIDDLE OLDER LOESS	OREL LOESS		PENULTIMATE GLACIATION, PH. 1	E. ANTIQUUS cf. TROGONTHERII
P IGl	GLACIAL TERR. 1				COOL OSCILLAT'N; PENULTIMATE INTERGLACIAL	E. ANTIQUUS C. ELAPHUS
ApGl2	PREGLACIAL T. I	LOWER OLDER LOESS	TILIGUL LOESS	ELSTER	ANTEPENULT. GLAC. 2	E. TROGONTHERII MEG. VERTICORNIS RANGIFER
		MAUER SANDS				
ApGl1	?PREGLACIAL T. II		?SULA LOESS		ANTEPENULT. GLAC. 1	
		?MAUER SANDS			ANTEPENULT. INTERGL.	E. MERIDIONALIS E. cf. TROGONTHERII E. cf. ANTIQUUS C. ELAPHUS M. VERTICORNIS HIPPOPOTAMUS MACHAIRODUS
EGl2	?PREGLACIAL T. III		?SULA LOESS		EARLY GLACIATION, PH. 2	
	?PREGLACIAL T. IV				EARLY GLACIATION, PH. 1	
	?PREGLACIAL T. V				AN EARLIEST GLACIATION? ?PHASE 3	
	?PREGLACIAL T. VI				?PHASE 2	
	?PREGLACIAL T. VII				?PHASE 1	

FIG. 24.—Attempted correlation of the chief deposits of the periglacial area of central and east Europe. Compare Fig. 17.

type of soil. This can only mean that the climate of west Europe had a tendency towards the Mediterranean climate, with hot and dry summers, but, unlike the chernozem areas, with mild winters. The distribution of chernozem, brown-earth and sub-Mediterranean brown-earth in the Last Interglacial suggests that the climate was, for some considerable time,

* For this very reason, it has been called *argile rouge* by the French.

characterized by summers hotter and drier than at present, whilst the general distribution of oceanic and continental conditions over west, central and east Europe was about the same as to-day. Faunal and floral evidence corroborates these conclusions.

The Last Interglacial was not a uniformly mild period. The Fourth Glacial Terrace of Thuringia has supplied evidence for a cold oscillation. This was apparently less intense than the cold phases of the Third and Fifth Glacial Terraces; although climatic aggradation took place in certain areas, no loess was formed, and the fauna contained species which would not withstand a severely cold climate. The Fourth Glacial Terrace is, perhaps, confined to Thuringia, but the Danish Middle Bed of the Last Interglacial affords a most important parallel, and so does the oscillation of the sea-level which separates the two Monastirian high levels of the Last Interglacial.

Succession of Climatic Phases.—Thus, the deposits of the periglacial area of central and east Europe supply evidence for the following succession of climatic phases (Table, Fig. 24, to be compared with Table, Fig. 17).

The Last Glaciation consisted of two phases, followed by a third, less intense, phase which was closely linked with the second.

The Last Interglacial was long and had dry and hot summers for some time; it was interrupted by a cold oscillation of minor intensity.

The Penultimate Glaciation consisted of two phases, of which the second was very intense.

The Penultimate Interglacial was long, and weathering intense; it was interrupted by at least one cold oscillation of minor intensity, possibly even less intense than that which occurred during the Last Interglacial.

It is probable that the Antepenultimate Glaciation also comprised two phases, the second of which equalled in intensity the second phase of the Penultimate Glaciation. The first phase would be represented by the Second Preglacial Terrace; its fauna and other evidence show that it *post*dates the Antepenultimate Interglacial.

Previous to the Antepenultimate Glaciation, at least five cold phases have been established. They are possibly the equivalents of the five morainic phases grouped in the Günz and Donau Glaciations of the Alps.

The periglacial area of central and east Europe has supplied evidence showing that the old division of three main glaciations (preceded by at least one more in the Alps) is substantially correct. It has, however, revealed that each of them consisted of two major phases and that, in addition, several minor cold oscillations occurred. It has also shown that, preceding the earliest large Scandinavian ice-sheet (which covered or destroyed any evidence of earlier cold phases in the *glaciated* area), several further cold phases occurred.

These results are remarkably consistent with those obtained in the Alps in recent years, especially by Eberl (see p. 47).

F. LOESS AND SOLIFLUCTION DEPOSITS OF NORTH FRANCE.

Parts A to E of this chapter have shown that central Europe affords optimum conditions for the reconstruction of the climatic oscillations of the Pleistocene.

Turning to west Europe, the first country to be considered is France, which is the classic region of prehistory, especially of the Palæolithic. Of all countries, France has supplied us with the most complete succession of Palæolithic industries, and the French divisions of the Palæolithic have become the standard for the world. The same cannot be said of the chronology of the Pleistocene deposits, which remained in an initial stage until research was stimulated in northern France, chiefly by H. Breuil. He relied on Commont's earlier work on the Somme terraces. Valuable work on the connection of the fluviatile terraces of the Somme with the ancient beach-lines of the English Channel was carried out by de Lamothe. This subject will be considered later on (p. 236).

Breuil (1931) agrees with other continental workers in regarding the loess as an eolian dust deposited under cold and comparatively dry conditions. He notices, however, that precipitation (rain or snow) interfered with the deposition of the loess in northern France more than in other regions. There is plenty of evidence of occasional action of water upon the slopes on which loess was deposited, in the form of indistinct stratification and of small layers of pebbles or angular fragments of flint washed down by rain or meltwater of snow. These layers, which are called *cailloutis*, are often ephemeral features, and their importance as climatic horizons has been greatly exaggerated. They are not confined to the loess region of northern France, but are frequent for instance in the Rhine valley also.

Genuine solifluction has played a considerable part in the formation of the valley deposits of northern France. Breuil has always stressed the importance of the phenomena (1934), and perhaps even over-emphasized it in one or two instances. Nevertheless, most of the solifluction levels in the Somme valley are of more than local significance. Numerous sections in northern France show that, as a rule, a phase of solifluction preceded the formation of a sheet of loess which, in turn, was weathered and transformed into a loam at a later time. Such a cycle admits of only one interpretation; the climate turned cold and damp at first (frozen soil causes intense solifluction), then cold and dry (eolian dust = loess deposited under steppe conditions), and finally reverted to normal temperate conditions with abundant vegetation and loamy weathering (interglacial phase). This is the same cycle as observed further east, in Germany, but on the whole the climate appears to have been relatively damper (more oceanic) in France even during the glacial phases.

Loess Sections of Northern France.—The loess sections of northern France afford great opportunities for the investigation of the climatic phases of the Pleistocene. A large number of sections have been made known, chiefly by the Abbé Breuil, and many others have been studied by himself and Mr. Harper Kelley, but a detailed study of the many buried soils is still wanting. The following description, therefore, is confined to a few important sections (or rather groups of sections) which I have had the opportunity to study on repeated visits under the guidance of the above-named gentlemen, and of which I have taken samples which were subsequently studied in the laboratory.

St. Pierre-lès-Elbeuf.—No locality appears to be known in northern France where more than two Younger Loesses separated by an *indisputable soil* are observed *in one and the same section*. A typical instance for the

two Younger Loesses resting on older loess is the section of St. Pierre-les-Elbeuf on the Seine, not far from Rouen (Fig. 25). There are several pits in the slope of a spur at the edge of the valley of the Seine.

The lowermost pit is that of the Briquetterie Bigot. Here, two Younger Loesses rest on the weathered surface of an Older Loess. The Recent soil is a brown-earth, but the soil separating the two Younger Loesses is brownish-black and has crotovines in the sub-soil. It closely resembles a chernozem, but is more likely to be a wet-meadow soil. It is entirely free from calcium carbonate, as is the subsoil to a considerable depth.

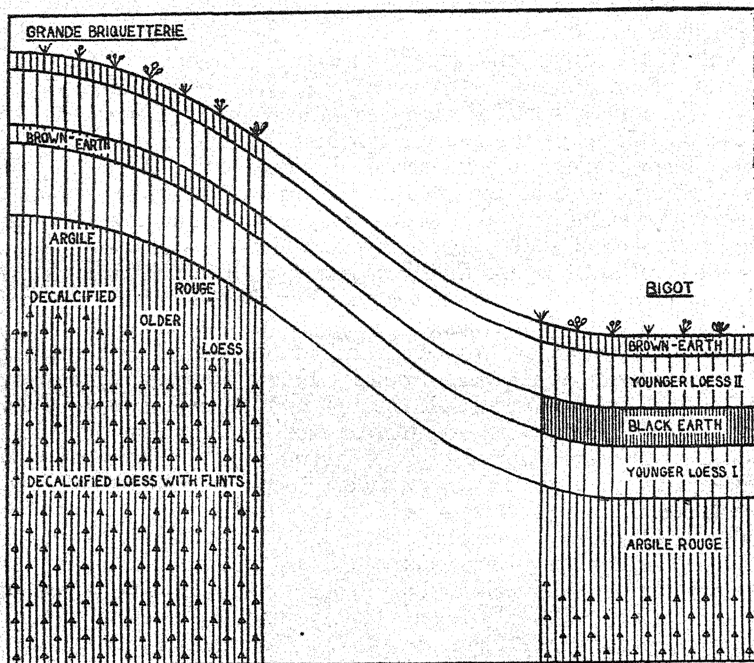


FIG. 25.—Combined sections of St. Pierre-les-Elbeuf, near Rouen, north France. Not drawn to scale, because of the great thickness of the section of the Grande Briquetterie and the considerable distance between the two sections. The top-soil is a brown-earth in both sections. The soil covering the first Younger Loess is a brown-earth in the Grande Briquetterie, on the upper portion of the slope, but in the Bigot section, on approaching the floodplain it changes into a black soil, probably formed under a wet meadow.

The weathered Older Loess is of the type called *argile rouge*. This is a loamy brown-earth soil which, however, is more reddish than ordinary brown-earth and reminiscent of the mediterranean varieties of this kind of soil. Argile rouge is the normal weathering of the Older Loess in south England, north France and west Germany, and indicates dry summers with temperatures slightly higher than the present.

The upper pit of St. Pierre is that of the Grande Briquetterie. In a section about 20 m. deep it reveals an astonishing thickness of Older Loess.

The two Younger Loesses are present as in the Briquetterie Bigot, but

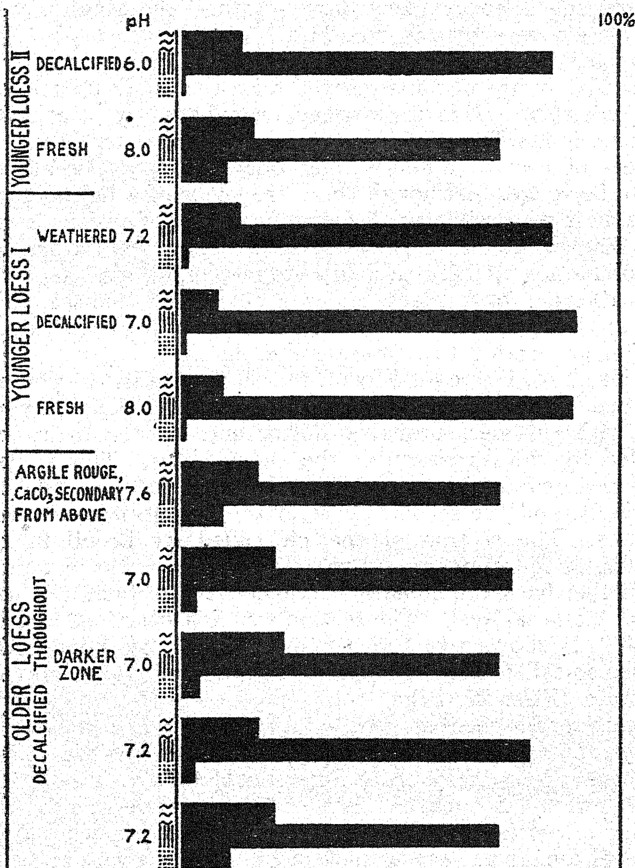


FIG. 26.—Mechanical analyses and pH-values of the section of the Grande Briquetterie, St. Pierre-les-Elbeuf, near Rouen, north France. Upper 8 metres of the section, showing Younger Loess II (its weathered surface removed), Younger Loess I, weathered on top, and Older Loess, completely decalcified and weathered to argile rouge.

In this and all succeeding diagrams of mechanical analyses three grades are shown, the " clay-grade " (wavy lines), smaller than 0·01 mm., which is liable to be affected by colloidal processes ; the " silt-grade " (vertical lines), of 0·01–0·1 mm. average diameter, which is most typical of the loess ; and the " sand-grade," of 0·1–2·0 mm. average diameter. The silt-grade is sometimes subdivided by a white line (e.g. Fig. 28), to the left of which is given the amount of material from 0·01–0·07 mm. characterizing the typical, fine-grained, loess. On the right is given the material from 0·07–0·1 mm. which plays an important part in the coarser varieties of loess. A line on the right-hand side of the diagram indicates 100 per cent. counting from the bases of the columns on the left. A continuous vertical line joining the bases of certain columns indicates that the deposits are directly superimposed.

The pH values indicate the degree of decalcification and weathering. pH = 7 is neutral, smaller values mean acid weathering, whilst higher values usually indicate absence of weathering and presence of calcium carbonate.

the separating soil is an ordinary brown-earth. The grading and the pH values of the beds are shown in Fig. 26.

The lower part of this section consists of Older Loess, but many metres of it are mixed with lumps of flints derived from the Chalk (which is the solid rock of the district). This unstratified or indistinctly stratified mass of loess with flint is a solifluction deposit; it is covered by Older Loess containing layers of coarse cailloutis, and finally by pure, weathered Older Loess, *i.e.* argile rouge. Although there are levels of a lighter shade in the Older Loess, it is impossible to discover further subdivisions of a climatic character. The entire complex was formed under cold conditions, with plenty of solifluction at first, and dry steppe conditions later on. Subsequently, weathering took place under a temperate climate, and a sub-mediterranean brown-earth soil was formed on top (argile rouge) whilst decalcification penetrated to a considerable depth.

The section of St. Pierre-les-Elbeuf, therefore, reveals the presence of not more than two Younger Loesses, preceded by a long phase of very intense weathering with summers probably hotter and drier than at present, in turn preceded by the formation of the Older Loess. This is the familiar central European succession of the two phases of the Last Glaciation, the Last Interglacial and the second phase of the Penultimate Glaciation.

MONTIÈRES.—The section of the pit called by Breuil Ballastière du Chemin-de-fer, at Montières, a suburb of Amiens, on the Somme, permits of tracing further back the climatic succession and of linking it with one of the phases of high sea-level. The section was first described and figured by Breuil (1934). It shows two Older Loesses buried by Younger Loess and resting on the so-called 30 m. terrace of the Somme. It is composed of the following strata (Figs. 27, 28):

J. (*Postglacial top-soil*, removed.)

I. *Younger Loess*, mostly removed. Where the investigated section is preserved there is 1 m. of Younger Loess but, laterally, it cuts through the Older Loess down to the gravel. Age of Younger Loess: Last Glaciation.

(H. *Period of erosion*: Valley cutting in connection with the lowering of the sea-level during the earlier part of the Last Glaciation.)

G. *Argile rouge fendillé* (upper soil of Fig. 28). This is the remnant of the reddish-brown weathering soil found universally on top of the Older Loess in northern France. Its parent material, however, appears here to have been a loess mixed with a considerable proportion of sand, as revealed by mechanical analysis. Admixture of non-loessic material is further emphasized by the presence of a thin and interrupted cailloutis near its base. The preserved thickness of this soil varies from 0·5 to 1·0 m.

F. *Fresh upper Older Loess* (middle loess of Fig. 28). This loess is impure, too, though to a less degree than (G). It is decalcified in its upper portion. Only 0·5–0·7 m. are preserved; enough, however, to prove that the phase of humid weathering evidenced by (E) was followed by a cold phase with deposition of loess.

E. *Lower soil, reddish and very humic.* This material also contains a fair amount of sand. Up to 2 m. are preserved, though mostly less, and in places fresh portions containing calcium carbonate occur underneath.

D. *Earlier Older Loess.* The fresh material mentioned under (E), dark yellow.

C. *Solifluction*, produced in the fluviatile gravels and sands of (B). First, more humid, part of the cold phase which caused the deposition of (D).

B. *Fluviatile gravels and sands* of the Middle Terrace of the Somme

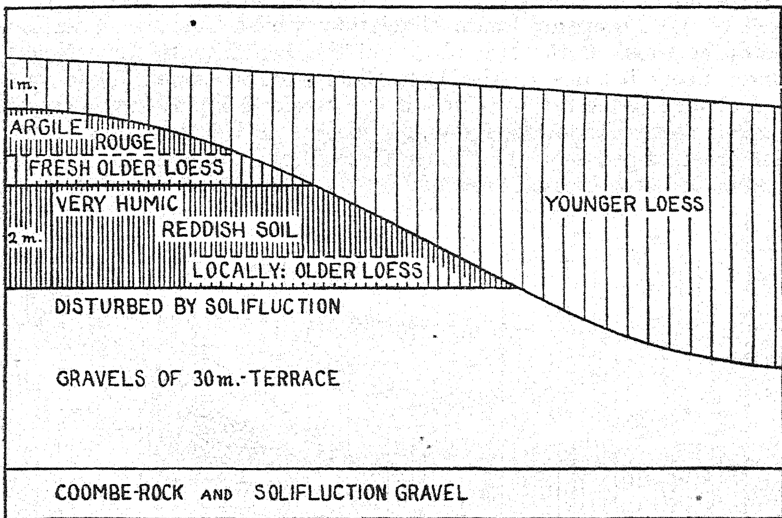


FIG. 27.—Section of the Carrière Chemin-de-fer, at Montières, near Amiens, north France. Back face of pit, with two Older Loesses, each covered by a soil. October 4, 1937. Compare Fig. 28.

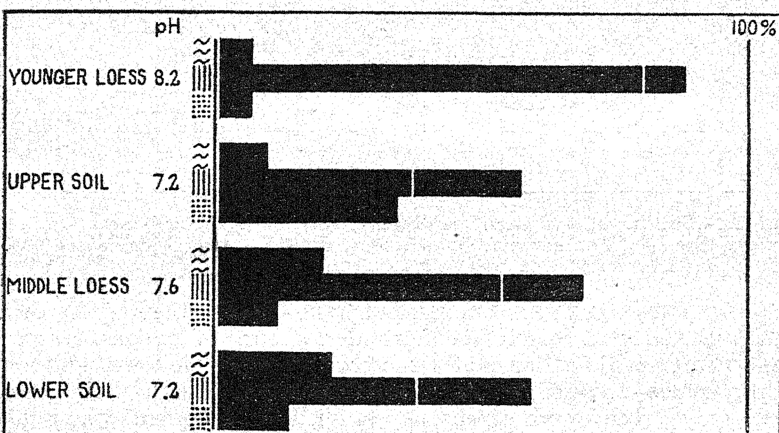


FIG. 28.—Mechanical analyses of the subaerial deposits of the Carrière Chemin-de-fer, Montières, north France. Explanation of diagrams, Fig. 26.

(" 30 m. Terrace "). Interglacial compensatory aggradation under the influence of a rising sea-level.

A. *Coombe-rock and other solifluction material* at the base of the fluviatile deposits. Cold phase preceding the mild period of the 30 m. Terrace.

The dating of the various deposits of this section can be based either on the 30 m. Terrace, or on the method of counting out the minimum age from above. The 30 m. Terrace runs into the Tyrrhenian sea-level (p. 231), of the Penultimate Interglacial. The solifluction (A), therefore, probably represents the Antepenultimate Glaciation, whilst the two Older Loesses can only be those of the two phases of the Penultimate Glaciation. The Younger Loess belongs to the Last Glaciation, as usual. It is apparent that the same dates are obtained if one works from the top downwards. The great value of the Chemin-de-fer section at Montières lies in the fact that it provides pedological evidence for two cold phases of the Penultimate Glaciation in north France.

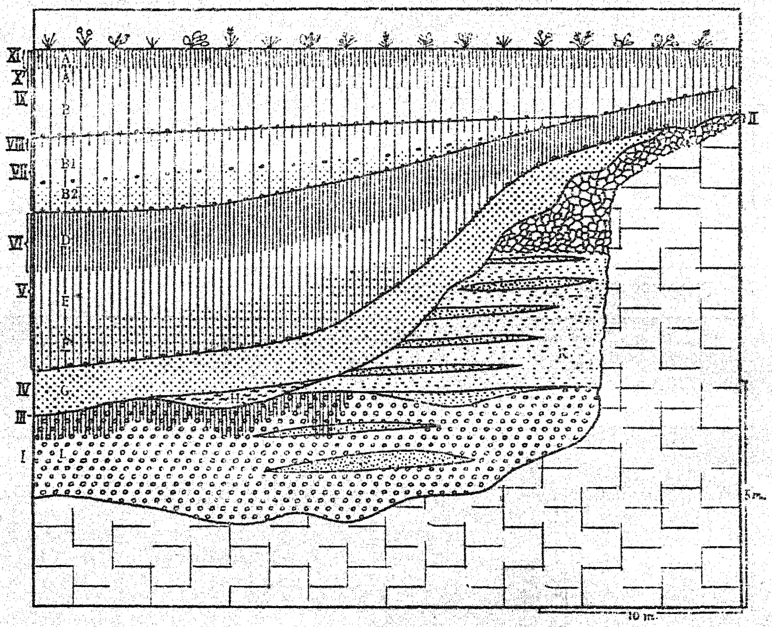


FIG. 29.—Section of the Carrières Bultel-Tellier, Saint-Acheul, near Amiens, north France. For explanation see text, p. 87. After Commont (1909*c*, 1912) and Breuil and Kozlowski (1931).

ST. ACHEUL, CARRIÈRE BULTEL-TELLIER.—The sections of the carrières Bultel and Tellier at Saint-Acheul, another suburb of Amiens, are perhaps the most important in Europe for the chronology of the lower Palaeolithic. though, in the present context, we are concerned with their geological aspects only. They were extensively studied by Commont, who published many papers on them (especially 1909*c*, and others between 1909 and 1913—compare bibliography ; further references in Breuil and Koslowski, 1931 ; Zeuner, 1936). Unfortunately, the sections are now in a state of disintegration, and it is to be hoped that the efforts of the Abbé Breuil to save from further destruction what is still left will eventually prove successful. Breuil and Koslowski's paper (1931, p. 471) contains a synthesis of Commont's earlier work as well as of their own. In the following summary Roman

numerals are used to designate the levels, since in Commont's original system of lettering several important deposits have not been lettered, and there is a slight discrepancy between his and Breuil and Koslowski's lettering (1931). For the purpose of reference, however, the lettering used by the last-named authors is added in brackets and also inserted in Fig. 29.

The pits Bultel and Tellier were dug into the deposits of the Middle or 30 m. Terrace of the Somme.

I. (L + K): The lowermost deposit is a gravel (L) with lenses of coarse sand. The gravel is covered by, and partly interstratified with, fluviatile sands (K) containing freshwater-shells, *Elephas antiquus*, and red deer. These gravels and sands represent the aggradation of the Middle Terrace. Their climatic character is interglacial.*

II. The sands (K) are covered by a coombe-rock, correctly interpreted by Breuil and Koslowski as formed under cold conditions.

The formation of the coombe-rock was followed, or partly contemporary with, a phase of erosion, during which the river cut down through the gravels of the Middle Terrace.

III. A lens of white chalky sand (H†) rests on the surface created by the preceding erosional phase. It is local however. It contains numerous shells (Commont, 1910*b*; Breuil and Koslowski, 1931), mostly freshwater species. The climate indicated by the shells was, according to Breuil and Koslowski, "moderately warm," and the country fairly humid, with deciduous trees and river marshes (p. 473). On a visit to the locality with the Abbé Breuil, on October 4, 1937, I was able to take a sample of a white chalky sand containing shells and underlying the "reddish sand" to be described presently. It is probable that this is the same layer as that seen by Commont in 1907 and first described by him in 1909*c*.

IV. A bed of "red sand" (G†) covers the deposits so far described, *i.e.* they rest on the eroded surface of the gravels, sands and the coombe-rock, whilst the white sands H appear to be more closely connected with them than with the underlying series. This is indicated (*a*) by the "weathering" which occurred before G was laid down and which passes *underneath* H according to Breuil and Koslowski's figure (1931, p. 472), and also by the presence of calcium carbonate, without a break, both in H and in G. Breuil goes so far as to regard G as the product of weathering of H (1939*b*), but this cannot be so since an examination of the material of G shows it to be an unweathered deposit. Breuil's assumption, however, emphasizes how closely H is linked with G.

The "red sands," G, are not easily interpreted. The material is regarded as sandy by Commont as well as by Breuil and Koslowski. On examination it proves to be rather of a loessic nature (Fig. 30), but it contains an admixture of numerous small pieces of chalk and is fairly resistant to the pick, owing

* A weathering which affected the gravels L is shown by Commont as well as by Breuil and Koslowski as passing *underneath* the sands K. If this can be confirmed, the weathering surface within the aggradation of the Middle Terrace of the Somme would afford an interesting parallel to the weathering of the Lower Loam in the 100 ft. Terrace of the Thames at Swanscombe.

† This lettering follows Breuil and Koslowski. In Commont (1909*c*) the lens of white shelly sand bears no designation and the overlying reddish sands (usually called G by Breuil and Koslowski) are called H. This explains why Breuil and Koslowski occasionally (1931, p. 473) refer to a "sable roux H."

to an impregnation with $CaCO_3$. This and the fact that the bed covers unconformably the slope, but is conformably covered by the Older Loess, renders it probable that it was formed as some kind of hill-wash during the initial stage of the cold phase of the Older Loess, at a time when chemical weathering began to be superseded by mechanical weathering. The upper portion of the bed G indeed appears to have suffered from trailing, which indicates solifluction.

The "red sands" G are important because of their archaeological contents. At the very base of the "red sands" G, on the "weathered" surface of the older series, a Palæolithic site was found, known as the "Atelier Commont." The accompanying bones are poorly preserved, which suggests that they were subjected to weathering before the bulk of the red sands was deposited, and that they belong to the same mild phase as the weathering horizon. The fauna, which comprises *Elephas antiquus* and red deer, confirms this view.

It is evident, therefore, that the cold phase of coombe-rock formation and erosion was followed by a mild phase.

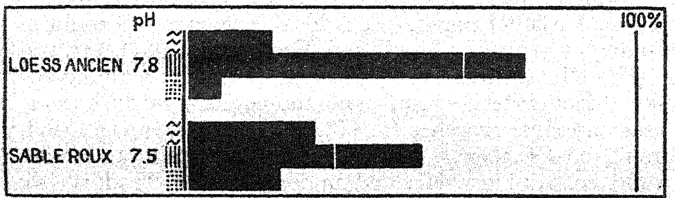


FIG. 30.—Mechanical analyses of the Red Sand (G) and the Older Loess (E + F), of the section Bultel-Tellier, Saint-Acheul, north France. Explanation of diagrams, Fig. 26.

V. The "red sands" are covered by Older Loess (Fig. 30). There is a cailloutis at its base, and the lower portion (F) is much sandier than the upper (E), which is a typical Older Loess. There are large concretions of calcium carbonate in the Older Loess, as elsewhere.

VI. The Older Loess is deeply weathered, the soil being called "argile rouge" (D).

VII. There are two Younger Loesses at St. Acheul. The first Younger Loess is sandy in its lower portion (B_2), and typically loessic in its upper (B_1). At its very base a cailloutis occurs, with mammoth, woolly rhinoceros and reindeer.

A second, weaker, cailloutis is intercalated between B_2 and B_1.

VIII. A short period of loamy weathering followed the deposition of the Younger Loess I.

IX. The second Younger Loess (B) begins with another horizon of cailloutis.

X. Postglacial weathering (A) modified the upper portion of the Younger Loess II.

XI. Re-deposition, probably due to ploughing, affected the uppermost level of A (A_1).

Thus the section of the carrières Bultel-Tellier at St. Acheul supplies evidence for the following climatic phases:

Two phases of the Last Glaciation, evidenced by the two Younger Loesses.

A prolonged period of intense chemical weathering, preceding the Last Glaciation and post-dating the Older Loess: the Last Interglacial.

The Older Loess cannot be later than the second or main phase of the Penultimate Glaciation.

It was preceded by a mild phase, a cold oscillation which can only be the first phase of the Penultimate Glaciation, and by—

A prolonged mild period during which the gravels of the Middle Terrace were aggraded. This period appears to have been another major interglacial, and since other deposits supply evidence of a yet earlier major interglacial phase, that of the Middle Terrace of St. Acheul must have been the Penultimate Interglacial.

This sequence agrees completely with those of other districts, and it provides further evidence for the duplication of the Last as well as of the Penultimate Glaciation.

High Terrace, St. Acheul, Carrière Fréville.—The carrière Fréville at St. Acheul permits of extending backwards the sequence established in the carrières Bultel-Tellier. It is part of the High, or 40 m. Terrace of the Somme. The section (Ladrière, 1890; Commont, 1909*c*; Breuil and Koslowski, 1931) rests on the Chalk and is composed as follows:

I. The earliest stratum is the lower gravels (L_1). In the same deposits in the rue du Comte-Raoul, Breuil (1939*a*, p. 25) found a molar of a primitive *Elephas antiquus*, the same form which is present in the corresponding deposits at Abbeville, but absent from the gravels of the Middle Terrace.

II. The upper part of the gravels L_1 is altered by chemical weathering.

III. A deposit of white sand with lenses of gravel rests on the weathered surface of the lower gravels.

IV. Older Loess covers the fluviatile beds just described, no doubt with a considerable chronological gap. The cailloutis at the base of this loess is the product of denudation previous to the commencement of the deposition of the loess.

V. Argile rouge, weathered surface of the Older Loess.

VI. Younger Loess. It again begins with a cailloutis.

VII. Weathered surface of the Younger Loess.

The important feature of the Fréville section is the presence of a very old gravel, underneath sands and gravels which can be correlated with the sands and gravels of the Bultel-Tellier section. They are separated from the older gravels by a period of denudation and weathering. The older gravels thus represent a much earlier phase of aggradation.

Abbeville, Porte du Bois.—Twenty-five miles downstream from Amiens, not far from the neck of the present estuary of the Somme, lies Abbeville. The pits of the Porte du Bois, just outside this town, have been famous for many years. One of them, the carrière du Moulin-Quignon, is the veritable birth-place of the Palæolithic, since it was from here that Boucher de Perthes, in 1847, described for the first time human implements associated with extinct species of mammalia (Boucher de Perthes, 1849). Chronologically more important is the carrière Carpentier, from which d'Ault du Mesnil (1896) made known a fauna of mammals of a very early Pleistocene age (often regarded as Pliocene).

The section of the carrière Carpentier (Commont, 1910*f*; Breuil and Koslowski, 1931) is as follows:

I. The earliest deposit is a fluviatile gravel (L_1) with *Hippopotamus*, rhinoceros and *Equus* cf. *stenonis*. The hippo indicates a mild climate.

II. These gravels are covered by a greenish chalky sand with freshwater shells (M_1).

III. On this sand rests the "white marl" (M) with sandy layers, chalk pebbles and oolitic concretions of calcium carbonate. It contains a fauna composed of many early Pleistocene species and some Pliocene survivals (see p. 259), notably *Elephas meridionalis* and *Machairodus latidens* (sabre-tooth tiger). This type of fauna occurs in Europe up to the beginning of the Antepenultimate Glaciation, and one is particularly tempted to compare it with the Cromer Forest Bed (see Chapter X, p. 260).

IV. The white marl is separated from the upper gravel by a sharp erosional unconformity. Commont also observed a small bed of peat. The gap is emphasized by the difference in the fauna of the white marl and of the upper gravels.

V. The upper gravels (L) and sands (K) contain, apart from shells, *Elephas antiquus* (typical form, Pontier, 1928).

In other pits also this bed has produced *Elephas antiquus*, and *Dicerorhinus merckii* and *Hippopotamus*, but never mammals of Pliocene affinities. Breuil and Koslowski (1931, p. 461), therefore, hold the view that this bed is considerably younger than the white marl, and that it was deposited in an interglacial phase later than that of the white marl, and, finally, that it can be correlated with the sands K of St. Acheul, carrières Bultel-Tellier.

VI. A cailloutis covers the sands. The cailloutis is followed by an Older Loess, and both indicate a cold phase.

VII. The Older Loess is completely weathered and transformed into argile rouge.

VIII. Top layer, possibly containing some younger Loess.

Whilst the loess portion of the carrière Carpentier at Abbeville is even less complete than that of the carrière Fréville at Amiens, the two fluviatile series are of the greatest interest. In both pits there is an upper fluviatile complex with a typically Pleistocene fauna, superimposed on a lower fluviatile complex with a fauna containing Pliocene survivals. It is difficult to escape the conclusion that the lower complex in both places dates from a mild phase considerably earlier than that of the upper fluviatile complex.

The upper fluviatile complex, however, must at least be of the age of the sands and gravels of Bultel-Tellier, namely at least of the Penultimate Interglacial. One is therefore inclined to assign the lower complex to the Antepenultimate Interglacial, a date which has been suggested and defended by Breuil for some time, and which is supported by the palæontological evidence also.

The question remains, however, whether unambiguous evidence can be brought forward for a cold period separating the gravels of the High Terrace with *E. meridionalis* from the gravels of the Middle Terrace with typical *E. antiquus*. The break between the lower and upper fluviatile series both in the carrière Carpentier and the carrière Fréville proves that denudation and (or) erosion removed some of the older material and that weathering

took place. Since the deposits are fluviatile, the denudational or erosional phase must have been connected with a lowering of the bed of the river. This, so near the sea, means a period of low sea-level. Whether this low sea-level phase was coupled with a period of cold climate cannot be ascertained from the two sections themselves, though Breuil (1939*b*, p. 34) claims that " a solifluction corroded the marl." It is noteworthy, however, that Breuil (1939*b*, p. 35) found " an important basal solifluction of coombe-rock " with implements " crushed by solifluction," underlying the deposits of the Middle Terrace. This shows that a *cold* phase preceded the formation of the Middle Terrace gravels and sands. This cold phase can only be the Antepenultimate Glaciation.

Summary of Climatic Divisions.—The evidence given for the climatic phases observed in the loess and solifluction deposits of north France could easily be amplified. The few sections discussed in this context, however, suffice to show that the climatic subdivisions of the Pleistocene of north France are the same as those of west Germany. In particular, there are two phases of the Last Glaciation, a long Last Interglacial with comparatively hot and dry summers, the Penultimate Glaciation with two phases, the Penultimate Interglacial, the Antepenultimate Glaciation and the Antepenultimate Interglacial. The last-named mild period exhibits a fauna with certain Pliocene survivals in north France as in west Germany, *Machairodus* being particularly typical.

As is to be expected, there is more evidence for subdivisions of the cold periods in the later half of the Pleistocene, and the duplication of the Last and Penultimate Glaciations is clear. The question arises whether the Antepenultimate Glaciation, too, comprised two cold phases, and whether the Early Glaciation antedating the Antepenultimate Interglacial was doubled or not.

As regards the Antepenultimate Glaciation, Breuil in his latest paper (1939*b*), p. 35 ; see also Bowler-Kelley, 1937, fig. on p. 27, and table, pp. 24, 25) distinguishes *two* levels of solifluction at the base of the Middle Terrace. The earlier of these is the one mentioned (see above) as containing crushed implements. Separated from it by " a level of sand and small gravel ; fluviatile stratification " is found " a level of badly stratified gravel with boulders, a solifluxion generally completely washed out by the river, but having here and there masses of chalk, and the typical gravel of solifluxion, in heaps, against which the river has piled up oblique beds of washed out material." These two levels of solifluction are considered by Breuil as representing two phases of the Antepenultimate Glaciation (his table, p. 38). He does not, however, state the locality where these conditions have been observed.

As regards the Early Glaciation, no subdivision has been established. There is " the clayey coombe-rock and coarse angular gravel at the base " of the High Terrace at Abbeville (Breuil, 1939*b*, p. 34), proof of a cold period antedating the fauna with Pliocene survivals, but no subdivision is recognizable. In his table (1939*b*), Breuil enumerates, with a query, a further solifluction phase after the fluviatile series with Pliocene survivals, but earlier than the basal solifluction of the Middle Terrace, calling it Pre-Mindel. By this is evidently meant the break IV (p. 90) separating III and V in the carrière Carpentier. There is no conclusive evidence for cold conditions

in this level, much of the suspected solifluction and "ice-cracks" being due to the unequal dissolution of the underlying marl.

Breuil's Latest Divisions of the Last Glaciation.—Until 1936 Breuil distinguished the same two Younger Loesses as defined here. In 1936, however, he introduced further subdivisions of the Younger Loess, making in all four younger Loess phases, each of which is said to be preceded by a phase of cailloutis formation (Breuil, 1936, p. 10; Bowler-Kelley, 1937, p. 8; Breuil, 1939*b*, p. 36). Of these, the two upper correspond to our Younger Loess II, and the two lower to the Younger Loess I. Unfortunately the sections on which these sub-subdivisions have been based have not yet been specified, and there is reason to assume that they occur in one or two sites which have not yet been published.

There is a fairly heavy solifluction (with coombe-rock in places) at the base of the Younger Loess. Three higher levels of "solifluction" are represented by cailloutis only; they are not found everywhere and are often replaced by blackish "humic layers." This combination of a hillwash with swampy layers is characteristic of the slopes of small vales in which no floodplain was formed, and it is probable that at least some of the dividing horizons of Breuil (1936 and later) are of this type. A most instructive counterpart is offered by Wallertheim, where a swampy layer is enclosed in the Younger Loess I, and where it proved to have been formed in a fairly cold climate, late during the first phase of the Last Glaciation. The fact that Breuil's new dividing horizons are described by himself as solifluction phases, shows that they cannot represent major oscillations with a mild climate. In order to establish these, it will be necessary to discover genuine buried soils of the brown-earth or similar types. Of these, only *one* has so far been observed in northern France, as described above (p. 84). Thus, the minor subdivisions of the Younger Loess recently introduced by Breuil do not appear to mark major climatic oscillations, although it is possible that they are of local significance.

G. TERRACES OF THE SOMME.

Up to this point it has been possible to avoid raising the question of the altitudes of the fluviatile deposits, their grouping into terraces and their relations to the Postglacial river and the sea-level. This somewhat extensive subject has now to be considered, since it supplies confirmatory evidence for the glacial and interglacial phases, and helps in elucidating the complicated process of valley formation of a river subjected to fluctuations of the sea-level (compare p. 21). It is particularly important in view of the great part played in the British chronology by the terraces of the Thames.

It will be remembered that the terraces of those rivers of central Europe which afford chronological evidence were all of the climatic type. The terraces of the Somme, however, are eustatic, at any rate in the lower course of the river; they depended on changes of the sea-level. Consequently glacial phases are evidenced by erosion in the lower part of the valley, and the aggradations chiefly date from the earlier parts of the interglacial phases.

The terraces of the Somme have been monographed twice, by Commont (1910*e*), who did the pioneer work, and by de Lamothe (1918), who applied

his extensive knowledge of the Mediterranean region. The views of these two authors differ in certain respects, although they were in close touch with each other. This alone shows that little can be wrong regarding the facts, and that it is only their interpretations that differ.

The differences of opinion between Commont and de Lamothe are very interesting from the methodological point of view. Commont was a local worker and concentrated on the surroundings of Amiens. Here he found the fluviatile deposits roughly grouped at certain levels above the floodplain of the present river. He also found that there is a buried channel underneath the present floodplain. Since the surfaces of the older fluviatile deposits are almost everywhere partly denuded and covered by later subaerial deposits, he defined his levels by the rock-benches on which the fluviatile deposits rest, measuring their height above the rock-bench of the latest aggradation, which is the bottom of the buried channel. At Amiens he distinguished in this way the following levels :

The High Level ; fourth, or 55 m. Terrace,
The High, or 40 m.-Terrace (sometimes called 45 m. Terrace),
The Middle, or 30 m. Terrace, and
The Low, or 10 m. Terrace.

The heights are those above the bottom of the buried channel ; not those above the floodplain, nor the absolute heights. Some confusion has arisen from a misinterpretation of these figures.

Breuil and Koslowski (1932, p. 27) have subdivided the Low Terrace into an upper and a lower Low Terrace, the latter also being called the 5 m. Terrace.

In extending his investigations to other parts of the Somme, especially to the Abbeville district, Commont retained the terms established at Amiens, and reconstructed the terraces of the river by continuing the benches observed at Amiens parallel to the bottom of the sunk channel. The result was a system of terraces parallel among themselves, but crossed at an angle by the modern floodplain with its much smaller gradient (Fig. 31). Commont did not consider, however, the question whether the surfaces of the aggradations were parallel to the benches or not. He assumed they were, and in this respect he was mistaken. Yet, as regards the sloping of the rock-benches of the terraces, Commont's system (apart from questions of detail) essentially reproduces the levels to which the Somme had cut down at certain phases of low sea-level which, according to the eustatic theory, were phases of a cold climate. That this is correct is shown by the universal presence of a *basal* solifluction on the benches. Conversely to the central European terraces, those of the Somme *begin* with a cold deposit and have a warm fauna in their *upper* horizons.

De Lamothe, having studied the high (interglacial) sea-levels of the Mediterranean, approached the problem of the Somme terraces from a very different angle. He argued that the *surfaces* of the sheets of aggradation should be used in the reconstruction of systems of terraces. These surfaces (obtained from the highest levels of recognizable fluviatile activity in the sections) run into certain ancient high sea-levels at the mouth of the Somme. Their gradients diminish downstream, as should be expected of an evenly-graded river, but their average gradients are much smaller than those of

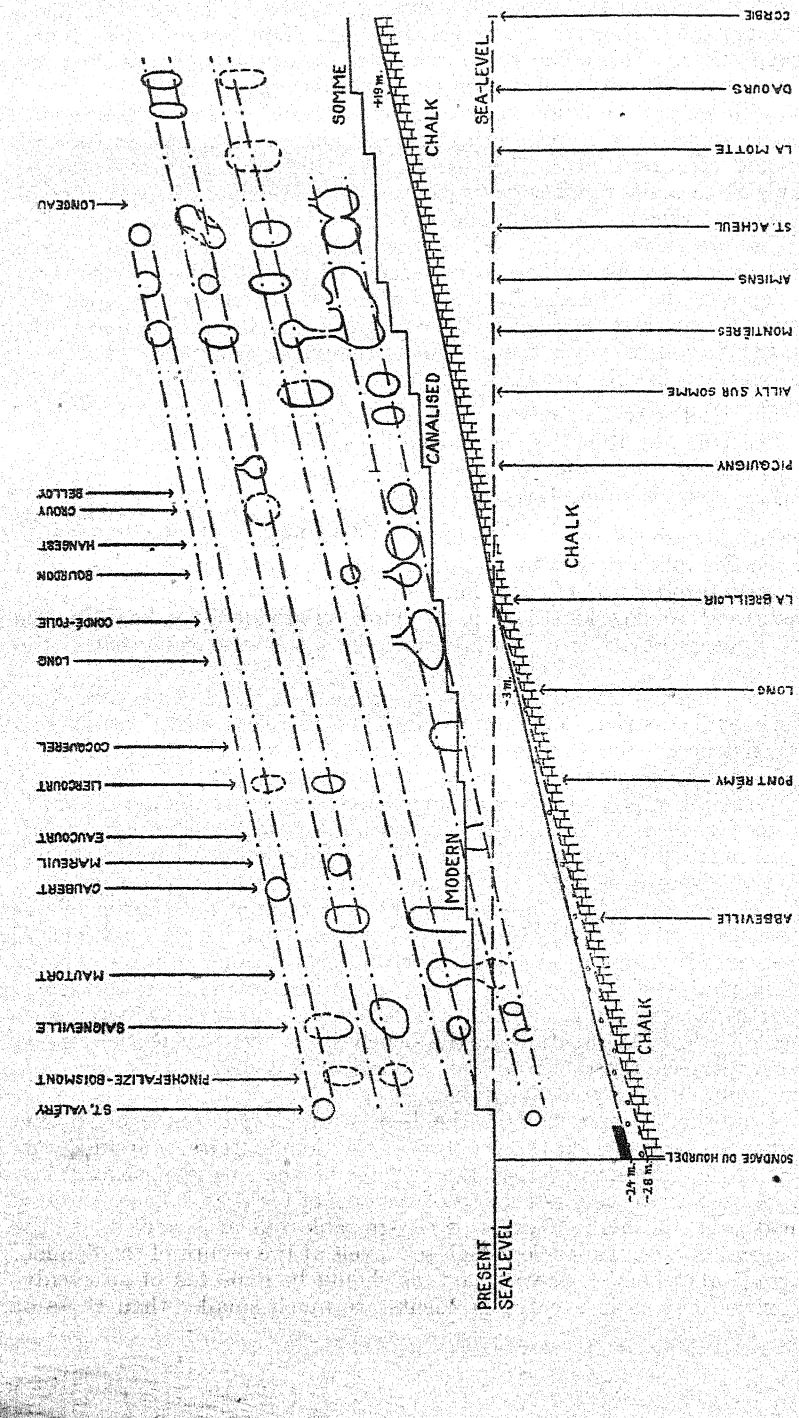


FIG. 31.—The terraces of the lower Somme as reconstructed by Commont. After Commont (1910*e*).

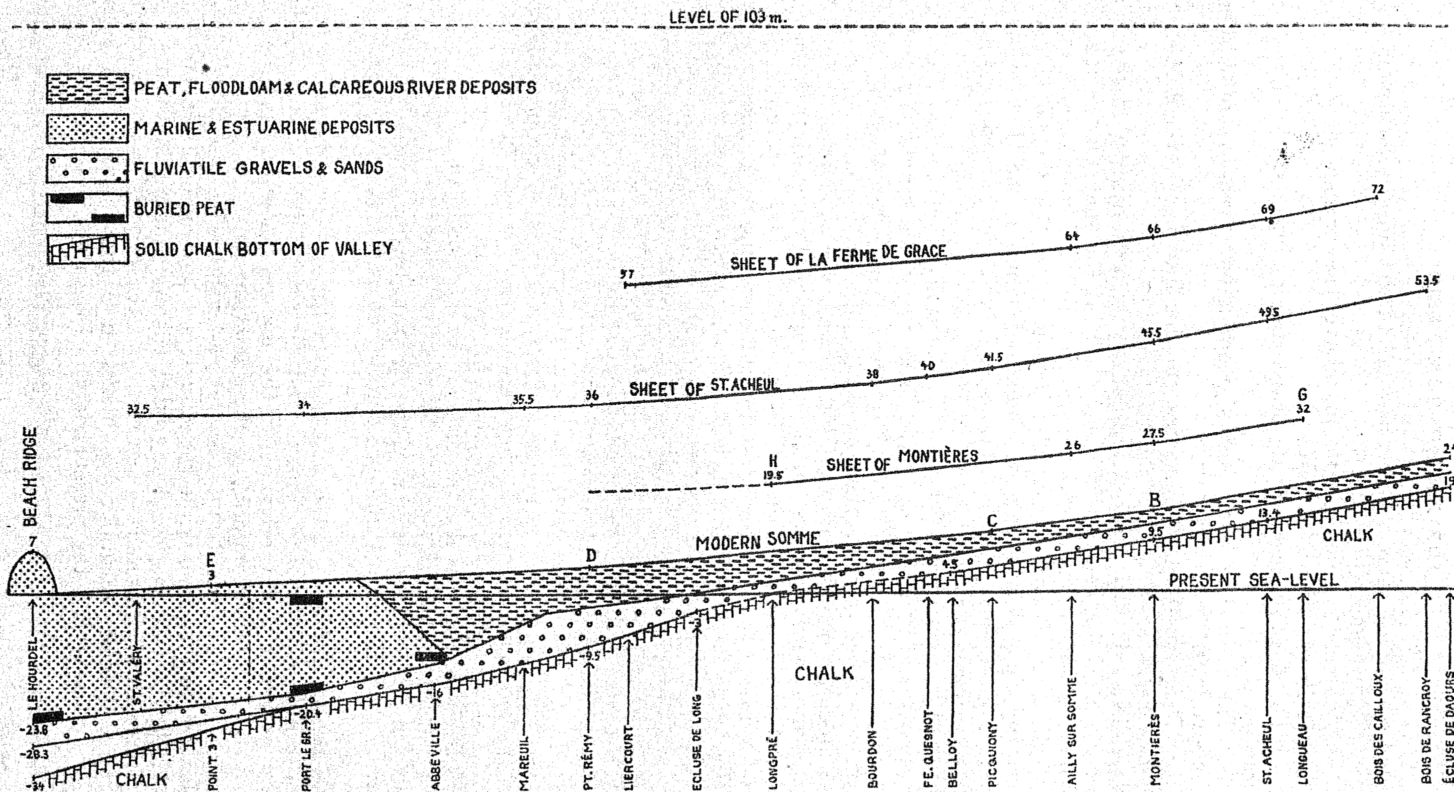


Fig. 32.—The terraces of the Somme as reconstructed by de Lamothe (1918). For interpretation of this and preceding figure compare p. 92.

the benches, and they are roughly parallel to the present floodplain. De Lamothe distinguished (Fig. 32):

The marine level of 103 m. above the present sea-level. (No fluviatile deposits preserved.)

The sheet of La Ferme de Grace, running into a sea-level 57–58 m. above O.D.

The main sheet of St. Acheul, running into a sea-level of 32–33 m. above O.D.

The main sheet of Montières, running into a sea-level of 18–19 m. above O.D.

At Amiens, de Lamothe's aggradation surfaces can be linked with Commont's benches, the sheet of Montières being the final stage of aggradation following the cutting of the bench of the 10 m. Terrace (Low Terrace), that of St. Acheul, correspondingly, belonging to the Middle or 30 m. Terrace, and that of la Ferme de Grace belonging to the High or 40 m. Terrace. The higher levels of Commont's and de Lamothe's systems cannot be connected reliably.

Buried Channel of the Somme.—It is fortunate that the buried channel of the Somme and its filling, up to the Recent deposits, supply the complete history of a cycle of fluctuation of the sea-level. The knowledge gained here can be applied to the earlier phases.

The modern floodplain of the Somme (*i.e.* the floodplain before the canalization of the river) is the surface of an aggradation which took place in late glacial and Postglacial times. It was built in response to the rise of the sea-level from the very low level it occupied during the maximum of the Last Glaciation to its present height. The gradient of the floodplain is now slight and decreases downstream.

At the maximum of the Last Glaciation, however, the Somme descended steeply to the low sea-level of that time, and a channel was eroded, linking the low sea-level with the river's course higher up the valley. Had sufficient time been available, a complete new valley-bottom with an evenly decreasing gradient would have been carved out, but the profile reconstructed by de Lamothe (Fig. 32) is discontinuous, and shows that the erosion had only worked backed to near Longpré, when another rise of the sea-level prevented further erosion. Below this knickpoint, the gradient of the bottom of the channel is much steeper than the gradient of the floodplain of the present Somme; above it, the gradient of the rock-bottom of the valley is about the same as that of the surface of the deposits resting on it. The exact position of the knickpoint cannot be determined, but is known within fairly narrow limits.

The *average* gradient of the floodplain of the modern Somme between Daours (8 miles upstream of Amiens) and the sea is 0·032 per cent., whilst the average gradient of the bottom of the channel below Longpré is about 0·18 per cent. Above Longpré it is about 0·03 per cent.

Eustatic Cycle of a River.—As the sea-level rose because of the return of meltwater to the ocean while the climate was improving after the maximum of the Last Glaciation, the eroded channel was gradually filled in. This process slowly extended upstream, and the gravels, peats, estuarine and marine deposits naturally are thickest near the mouth. Over 30 m. have been measured at the present mouth of the river. Above the knick-

point, however, very little was added, and not more than 3–4 m. of gravel floodloam and peat are found here covering the rock-bottom of the valley.

Thus, the complete cycle of a river from interglacial to interglacial, near its mouth where it is affected by the fluctuations of the sea-level, is as follows: As the climate becomes colder, the sea-level drops, and erosion works upstream, cutting a channel with a gradient steeper than that of the preceding floodplain. This erosion will be most intense when the sea-level is at its lowest and the climate coldest. Solifluction deposits cover the slopes of the valley. With the beginning of the amelioration of the climate the sea-level begins to rise, the sea will enter the mouth of the eroded channel and mixed marine and fluviatile deposits will gradually fill it. In the meantime, however, the knickpoint is still being worked back by erosion. This erosion continues into the new interglacial (unless it is overwhelmed by deltaic deposition), and the knickpoint becomes the starting-point for the climatic erosion typical of inland rivers during the first part of an interglacial, as described in discussing the central European river terraces.

When the sea-level has reached its highest point, at the climax of the interglacial, the floodplain of the river will approach the horizontal towards the mouth, and its gradient will be very small. Below the knickpoint, therefore, a very typical set of conditions is observed: resting on a bench sloping steeply down to below the present sea-level, deposits are found which increase in thickness downstream, and the surface of which runs into an ancient high sea-level. These deposits are cold at the base and warm higher up, the uppermost fluviatile beds dating from the climax of an interglacial.

Some distance above the knickpoint, however, the normal cycle of climatic erosion and aggradation will have prevailed. Here the river aggraded while the climate became colder and eroded while the climate became warmer after the maximum of a glaciation, and continued to erode until the climate began once more to deteriorate.

In the part of the river where the knickpoint is situated conditions are bound to be very complicated and entirely dependent on the speed and power of action of the two rival cycles involved.

Not counting the subphases of the glaciations, the Somme has gone through these cycles four times at least. Below the knickpoint the rock-benches slope down so steeply that the aggradations of later interglacials often cover the denuded remains of earlier aggradations left on their rock-benches, as is the case for instance in the carrière Carpentier at Abbeville. A careful determination of the heights of the rock-benches and a plotting of the results on a longitudinal profile should clearly bring out the channels cut during the glacial phases previous to the Last Glaciation. This has, to my knowledge, not yet been done for the Somme, so that at the present moment we have to be satisfied with a somewhat scanty piece of evidence.

Gradient of the Rock-Bench of the High Terrace.—At St. Acheul, carrière Fréville, deposits of the High Terrace are preserved beneath the aggradation of the Middle Terrace, whose surface just reaches this level. These High Terrace gravels are, of course, the remains of an aggradation which once reached up to the top level of the High Terrace as determined by de Lamothe, and was eroded and denuded during the low-level phase which separated the High and Middle Terraces. The rock-bench beneath the High Terrace gravels of the carrière Fréville, therefore, is that of the

High Terrace, and has nothing to do with the Middle Terrace. From data supplied by various authors, it lies at about 45 m. O.D.

In the carrière Carpentier at Abbeville, 25 miles downstream, the same deposits are observed again, and the rock-bench of the High Terrace proves to be at about 29 m. O.D. From these values the approximate gradient of the bench of the High Terrace is obtained as 0·04 per cent. This is appreciably higher than the gradient of the surface of this terrace (0·032 per cent.).

The reason why it is so difficult to disentangle river terraces of the eustatic type is now obvious. Since in a system of climatic terraces of an inland river the terraces run practically parallel to one another and parallel to the floodplain and, in addition, their benches are parallel to the aggradation surfaces, it is comparatively easy to establish a succession of events. In a eustatic system, however, there is a divergence downstream, the degree of which depends on the heights of the sea-level phases involved. Moreover, in eustatic rivers the majority of good sections are crowded into the neck of the estuary, where conditions for preservation were better than further downstream and where, owing to the frequency of human settlement in such places, more pits are available for examination. Unfortunately, this is just the stretch of the river where knickpoints are likely to occur. The position of knickpoints depends on the intensity and duration of the erosional phases which created them, and some lie higher upstream than others. In this zone, therefore, there is likely to be some overlap of the climatic aggradation and erosion from the river's course above the knickpoint and of the eustatic erosion and aggradation from downstream. Very complicated conditions are the inevitable result. River systems of this type, therefore, cannot be regarded as very suitable for the reconstruction of the climatic chronology of the Pleistocene. It is interesting to note in this context that the climatic chronology of Breuil and other workers in northern France is largely based on the character of the deposits, and not on the river terraces as such.

North France: Summary.—In spite of these difficulties, de Lamothe's work has enabled us to link the climatic chronology of northern France (as summarized on p. 99) with the fluctuations of the sea-level. Since the climatic chronology of France agrees well with that of central and east Europe, it provides the means for connecting the climatic phases of the Pleistocene of temperate Europe with the various phases of high sea-levels established in many parts of the world, and therefore an ultimate basis for world-wide correlation. This matter will be treated more fully in Chapter IX. The succession of climatic phases established in northern France is summarized in the table, Fig. 33, which should be compared with the summary table (Fig. 24) of central and east Europe, and with that of the morainic areas (Fig. 17).

Pleistocene Chronology of the Temperate Part of the Continent of Europe.—Such a comparison shows plainly how consistent the results are which have been obtained in these various districts. It becomes evident that the climatic fluctuations were ubiquitous in the region so far considered.

The outstanding results, applying to the whole of temperate Europe, are as follows: The Last Glaciation is divided into two main phases, whilst in some districts a third, weaker, phase is recognizable.

The Last Interglacial was long and had a period of hot and dry summers.

It was longer than the Postglacial and longer than the interstadial between the two main phases of the Last Glaciation.

The Penultimate Glaciation comprised two main phases, of which the second appears to have been more intense than the first. On the whole, the Penultimate Glaciation was more intense than the Last Glaciation.

The Penultimate Interglacial was long and mild, climatically similar to the Last Interglacial.

CLIMATIC PHASE	SUBAERIAL DEPOSITS, WEATHERING	SEA-LEVEL, EUSTATIC RIVERS	FAUNA
LGl 3	WEATHERING AND DENUDATION	SEA RISING TO PRESENT LEVEL, RIVERS FILLING IN THE CHANNEL ERODED DURING LAST GLACIATION	
LGl 2	YOUNGER LOESS II SOLIFLUCTION	SEA LOW, RIVERS CUT "BURIED CHANNELS"	E. PRIMIGENIUS
	WEATHERING		
LGl 1	YOUNGER LOESS I SOLIFLUCTION	SEA-LEVEL LOW, RIVERS CUTTING	E. PRIMIGENIUS
LIgl	INTENSE WEATHERING (ARGILE ROUGE) AND DENUDATION	SEA RISING TO 19 m. RIVERS AGGRADING	E. ANTIQUUS
PGl 2	UPPER (MAIN) OLDER LOESS SOLIFLUCTION	SEA-LEVEL LOW, RIVERS CUT DOWN	E. PRIMIGENIUS
PGl 1	LOWER OLDER LOESS SOLIFLUCTION	RIVERS CUTTING DOWN	E. PRIMIGENIUS
PIgl	WEATHERING AND DENUDATION	SEA RISING TO 33 m. RIVERS AGGRADING	PRIMITIVE E. ANTIQUUS
ApGl	SOLIFLUCTION, TWO DISTINCT LEVELS ACCORDING TO BREUIL	SEA-LEVEL LOW, RIVERS ERODING	
ApIgl		SEA RISES TO 59 m. RIVERS AGGRADE	E. MERIDIONALIS MACHAIRODUS
EGl	SOLIFLUCTION		

FIG. 33.—Correlation of the subaerial and fluviatile deposits of the lower Somme area, north France.

The Antepenultimate Glaciation comprised two main phases. In intensity it rivalled with the Penultimate Glaciation.

The Antepenultimate Interglacial was mild, but its climatic character cannot be determined in detail. Its fauna contains Pliocene survivals.

The Early Glaciation comprised two phases in the Alps, but no evidence of this subdivision is preserved in the periglacial area or in the Scandinavian area.

Earlier glacial phases have been recognized in the Alps and in the periglacial area of Germany.

In the periglacial area of Germany a minor cold oscillation interrupted

the Last Interglacial, and one or two such oscillations appear to have occurred during the Penultimate Interglacial.

The succession of climatic phases just outlined applies to a wide region, and is firmly established by numerous *purely geological* observations. Nearly all the phases are evidenced by buried soils either of the chemical, or the physical, type of weathering, a method far more reliable than any other in the Pleistocene. Confirmatory evidence has been afforded by river terraces, glacial deposits, and fauna and flora. Only the duplication of the Early Glaciation, and the cold phases preceding it, have not been proved by means of soils, but by moraines and river terraces only.

The essence of this succession, which will henceforth be called the *detailed relative chronology,* is the probable triplication of the Last Glaciation and the duplication of each of the three preceding major glaciations. It will be seen later on that it provides the basis for an absolute chronology of the Pleistocene and, therefore, of the evolution of flora, fauna, and of man himself during this period of time.

CHAPTER IV

THE PLEISTOCENE CHRONOLOGY OF THE BRITISH ISLES

In Britain, Pleistocene stratigraphy has developed on more independent lines than on the Continent, largely because its geographical separation discourages correlation with other countries. But this is not the only difficulty.

At all times during the Pleistocene the British Isles had a relatively more oceanic climate than the remainder of Europe. This fact finds its chief expression in the dominance, during the glacial phases, of solifluction in Britain as against wind action (loess steppe) on the Continent.

Furthermore, in any given area on the Continent, the transgressing ice-sheet had a single origin, coming either from Fennoscandia or from the Alps while, in the British Isles, several centres of glaciation were active, the ice-sheets fusing or, in some districts, replacing one another in the course of a glaciation, and linking up repeatedly with the Scandinavian ice-sheet that came across the North Sea. It is much more difficult, therefore, to disentangle British than Alpine or north German moraines.

In view of these and other difficulties, the succession of climatic phases is less firmly established in Britain than on the Continent. It can be shown, however, that the relative chronologies of the two areas do, in fact, agree closely. In order to outline the British succession of climatic phases, the bare minimum of evidence has been quoted in the following paragraphs, sections and areas having been selected for their chronological significance only, disregarding their archaeological or other local import.

The discussion is best limited to two main groups of deposits: (A) the glacial deposits of East Anglia and Wales, and (B) the fluviatile deposits of the Thames Basin.

A. MORAINIC DEPOSITS.

Norfolk.—Norfolk is the classic land of morainic stratigraphy. In the middle of the last century S. V. Wood (father and son) studied the Mollusca of the *Crags*, the marine deposits which underlie the glacial deposits of the area. Two strata of boulder-clay were then distinguished and recognized as of glacial origin. In 1867 F. W. Harmer began the publication of a number of important sections from the neighbourhood of Norwich, partly in conjunction with S. V. Wood. All these sections show, in essence, the same picture, so that one of the oldest published (Harmer, 1867, p. 89, fig. 2) can be used as the prototype (Fig. 34). This section, across the Yare valley above Norwich, from Tuck's Wood Farm to Arminghall Wood, shows

on an even surface of the Chalk, on both sides of the valley, the following succession:

7. A sheet of upper, chalky, boulder-clay.
6. A stratum of sands.
5. A lower boulder-clay, the Norwich Brickearth.
4. Sands.

In neighbouring sections, beds 2 and 3, the Chillesford Crag, are present.

Sections of this kind have been interpreted as proving the occurrence of two glaciations following the deposition of the Crag series. That beds 5 and 7 are not merely minor oscillations of the same ice-sheet is shown, in the Norwich area, by the weathering of the lower moraine, *i.e.* the Norwich Brickearth. This argument has been used particularly by Boswell (1923, pp. 218–219), who says that " the latter deposit has the appearance of having been well weathered before the deposition of the sands and gravels on it, and it is usually thoroughly decalcified."

The separation of the two boulder-clays of the Norwich area by a full interglacial or interstadial is further, and independently, shown by the topographical position of the upper boulder-clay. Unlike the lower boulder-clay, the upper descends into the valleys, where it occurs in many places at a level lower than that of the Norwich Brickearth (Fig. 34). The cutting of the valleys of this part of Norfolk, therefore, must have taken place between the two glaciations. Sections testifying to this are numerous around Norwich, and have been described by Harmer (1867), Wood and Harmer (1869, 1877), Harmer (1902, 1910). The significance of this evidence was first recognized by Wood and Harmer (1869), discussed exhaustively by the same authors (1877), again by Harmer (1910, p. 119), and confirmed by Boswell (1923). It is certain, therefore, that a prolonged period of erosion intervened between two glaciations in the Norwich area.

A third argument in favour of the separation of the two glaciations by a long interval is provided by the sands which intervene between the two boulder-clays. In the majority of sections these sands appear to be glacifluvial, belonging either as an after-phase to the Norwich Brickearth glaciation or, more likely, as an advance-deposit to the upper boulder-clay glaciation. In some localities, however, mostly not far removed from the present coastline in the neighbourhood of Yarmouth, they contain marine shells.

The marine Mollusca of the so-called " Middle Glacial " sands have by some been considered as derived from the Crag, but Wood and Harmer (1872–4) held that they were contemporaneous with the sands, although redeposited within the same. A list of the shells found, for instance, at Billockby is given in Woodward (1881), and those found at Corton were studied by Harmer in 1902, and in his memoir of the Pliocene Mollusca (1914–1925). As late as 1928 Harmer reiterated this view, which has been favoured also by Boswell (1931, p. 92) and accepted by Baden-Powell and Moir (1942). The section in the sea-cliff at Corton, south of Yarmouth, is important because it shows the marine sands resting on calcareous " Norwich Brickearth," and covered by a blue Chalky-Jurassic boulder-clay. It is highly probable, therefore, that the sea stood at a higher level than to-day for some time during the inter-phase which separates the lower from the upper boulder-clay of this area.

Thus, weathering, valley erosion and marine transgression provide cumulative evidence for two independent glaciations of eastern Norfolk, and for an intervening interglacial of long duration.

CROMER AREA.—The area of Cromer, on the north coast of East Anglia, permits the sequence established in the Norwich district to be extended in both directions.

In the sea-cliffs both east and west of Cromer two types of moraine are found, capped by, or combined with, and sometimes separated by, sands and gravels. The lower moraine is called the Cromer Till, the upper, the Contorted Drift. The latter is clearly transgressive and occasionally cuts down into the Till and even reaches the Chalk, but as no weathering has been found on the surface of the Till, the two moraines may be deposits of two successive ice-streams of the same glaciation. This suggestion has been made repeatedly, and in Harmer's times the two together were regarded as the equivalent of the Norwich Brickearth.

A new phase in the investigation of the Cromer sections began when Boswell (1931) discussed the *pros* and *cons* of this correlation. In the following year, Solomon (1932) investigated the succession in great detail, and applied heavy mineral analysis in order to distinguish the strata. For convenient reference, his succession (which is composite) is repeated here :

H. 12.	Brown Boulder-Clay . . .	Hessle.
L. 11.	Ridge Gravel	Little Eastern.
L. 10.	Miscellaneous Brickearths . .	
i. 9.	Bacton Valley Gravel . . .	Interglacial.
C. 8.	Chalky Outwash Gravel and Sand	Great Eastern.
C. 7.	Chalky Boulder-Clay . . .	
C. 6.	Sands and Gravel . . .	
C. 5.	Glacial Lake Clays . . .	
N. 4.	Sands (Mid-Glacial) . . .	North Sea.
N. 3.	Upper Till	
N. 2.	Mundesley Sands . . .	
N. 1.	Lower Till	

Underlain by *Leda myalis* Beds, Forest Bed, etc.

From our present point of view his outstanding result is that most of the Till belongs to a glaciation earlier than that which produced the bulk of the Contorted Drift. He substantiated this distinction by the following arguments : (*a*) A considerable period of erosion must have intervened between the deposition of the North Sea Drift (=Till) and the advent of the Chalky Great Eastern ice-sheet (*i.e.* Contorted Drift ; Solomon, p. 269) ; (*b*) the contents of heavy minerals of the Till are distinctive (p. 245), whilst that of the Chalky Boulder-Clay is very variable (pp. 247, 260). In detailed sections, however, Solomon was compelled to disagree with earlier observers as to which of the two moraines is present. Some of the "Till" has been incorporated in the deposits of the later glaciation (p. 244), whilst some of the Chalky Boulder-Clay is classed with the Upper Till (p. 270). These local uncertainties, however, are insignificant, if only a single good section exists proving that two boulder-clays are separated by an interglacial or interstadial.

Recent work by Baden-Powell and Moir (1942) appears to provide one

or two sections of this kind. These authors describe from Runton, west of Cromer, marine fossiliferous sands underlain by the North Sea Drift and covered by a Chalky boulder-clay. The fauna of these sands agrees with that of Corton, south of Yarmouth, and it is emphasized that the shells cannot be derived from the Crag. The sands are termed the "Corton Sands."*

One point where the position of the Corton sands can be seen is at the gap of West Runton, where two synclines are filled with marine sands and gravels containing many shells. In the westerly syncline, Chalky boulder-clay is found on top of the sand. A second important exposure is in the gravel-pit at East Runton, where the succession (1) lower moraine, (2) sands and gravels with shells, (3) very chalky boulder-clay, can be established. When I visited this pit with Messrs. Baden-Powell, Kimball and Moir in July, 1939, the sand underneath the upper boulder-clay appeared to be deeply weathered, the weathering having taken place before the Chalky, unweathered, boulder-clay was deposited over it.

In spite of many local difficulties in identifying the members of the succession in individual sections, the general succession at Cromer appears to comprise a lower and an upper moraine separated by considerable erosion, by weathering and by a transgression of the sea. The same criteria were used to establish two glaciations for the Norwich area. As far as the available evidence goes, therefore, at least two great glaciations have passed over Norfolk, (1) that of the Norwich Brickearth and the Cromer Till, plus part of the Contorted Drift, and (2) that of the Chalky Boulder-Clay, with parts of the Contorted Drift. The terms adopted by Boswell (1936) will henceforth be applied to them, namely "North Sea Drift" Glaciation for the older, and "Great Chalky Boulder-Clay" Glaciation for the younger. The intervening interglacial may, in accordance with Baden-Powell and Moir, be termed the "Corton Sands" Interglacial.

THE CRAG SERIES.—The Till of the Cromer Coast overlies the well-known *Forest Bed Series* (the "Cromerian"), and this, in turn, the succession of the East Anglian Crags. These deposits have been studied repeatedly, notably by Wood, Harmer, E. T. Newton and Clement Reid. They were originally

(Cromer Till.)	Glacial.
(8) *Leda myalis* Bed .	Marine.
(7) Cromer Forest Bed .	Fluviatile-estuarine.
(6) Weybourne Crag .	Estuarine-marine.
(5) Chillesford Crag .	Fluviatile-estuarine.
(4) Norwich Crag . .	Estuarine.
(3) Newer Red Crag .	Marine shore deposit.
(2) Older Red Crag .	,, ,,
(1) Coralline Crag . .	,, ,,

* In the Cromer area they were regarded by many authors as younger than the second moraine, because of their occurrence in the coast section above some contorted drift (thus corresponding to Solomon's C8, Solomon, 1932, p. 249), though Wood, Harmer and Reid (1882) assigned to them the position which they possess according to Baden-Powell and Moir. East of Cromer, the Corton Sands may be represented by Solomon's N4, sands of marine appearance intercalated between the Till and the Chalky Boulder-Clay.

regarded as Pliocene, but since Ray Lankester's days (1912) they have with good reason been partly included in the Pleistocene by several authors.

Since it is impossible here to discuss the entire problem of the age of the Forest Bed and the Crags, the two points most important in the present context have been selected, namely (*a*) the palæontological age of the Forest Bed, and (*b*) the climatic succession evidenced by the Crag deposits. For reference, the sequence of deposits is given first (see table, p. 104).

THE AGE OF THE FOREST BED.—The fluviatile and estuarine sands, gravels and peats of the Cromer Forest Bed are separated from the moraine of the North Sea Drift by a complex containing the *Leda myalis* Bed (marine) and the Arctic Freshwater Bed. The relative position of these two is not clear. The Geological Survey considered the Arctic Freshwater Bed as the younger, but Solomon (1932) found reason to believe that the *Leda myalis* Bed was formed after the Arctic Freshwater Bed. Since both were formed under cold conditions, on the evidence of their fauna and flora (Reid, 1882, pp. 46, 83), the relative position matters little from our point of view. They tell of a cold climate reigning previous to the arrival of the ice of the North Sea Drift. Whether this was a separate cold phase, or only the beginning of the phase of the North Sea Drift, cannot be decided.

The underlying Forest Bed at Cromer* was formed in a temperate climate. This is shown by the abundant flora (Reid, 1882, 1890) and fauna (Newton, 1882). Geologically, the relative age of the Forest Bed is later than the entire Crag succession, but earlier than the North Sea Drift. Palæontologically, the fauna (see Chapter X, p. 260) provides some clue to the age. There are sixty forms of land-living mammals, and almost half of this number are known to have been extinct on the Continent by the time of the Elster Glaciation. Some of these are survivals from the Pliocene. The Forest Bed, therefore, belongs clearly to the early Pleistocene. The age relative to Continental deposits has been worked out in greater detail by comparing its fauna with faunas like Mosbach, Mauer, Süssenborn, the stratigraphical position of which is known (Zeuner, 1937). It has been found in this way that the Cromer Forest Bed is slightly older than Mauer near Heidelberg (p. 261).

MOLLUSCA OF THE CRAG SERIES.—The enormous number of bivalve and gastropod shells in the estuarine and marine Crags of East Anglia suggests a statistical analysis as a help in forming an idea of the climatic conditions under which the successive Crag faunas lived. This is a matter of some importance since, according to several authors, icebergs brought large erratics into the Crag sea. In spite of the many Mediterranean species, therefore, the Crag sea appears to have been cold at certain times. Boswell (1936) is prepared to admit the possibility of a cold phase in Crag times, but he considers that the shells merely indicate a steady fall in temperature. Ray Lankester (1912), however, was satisfied that glacial conditions set in at the beginning of the Red Crag deposit. This author pointed out the crucial difficulty in the climatic analysis of the Crag fauna. During the successive stages of the Crags, older Crag deposits were worked up by the sea and their shells incorporated in the later deposits. He further pointed out that in a contiguous series like the Crags, some species may have survived

* The Forest Bed at Bacton contains a colder fauna than that at Cromer and is perhaps later, possibly representing the Arctic Freshwater Bed of the Cromer area.

adverse conditions for some considerable time. It follows that the disappearance of species or subspecies is a bad indicator of climate. This is illustrated in our table below, by the "Mediterranean" group of shells, whose number decreases very gradually.

On the other hand, newly-appearing forms do not suffer from the impediments described; they are, therefore, good climatic indicators, provided they are numerous enough to point to a definite type of climate. Once they have appeared, however, they are subject to the same rules of redeposition and survival as are the older members of the fauna. Applied to the Crags, this means that a cold phase would be expressed by a sudden upward jump in the number of arctic shells, without subsequent conspicuous drop.

The following table of the composition of the Crag fauna is the modification of one published by Boswell (1931). Extinct forms are omitted, since they do not help in determining the climate. The number of living British species is reduced, or brought up to 100, the other groups being reduced or increased in proportion (Zeuner, 1937).

	Total number.	Relative numbers.		
		Living British.	Arctic.	Mediterranean.
Forest Bed	19	100	0 (?7)	0
Weybourne Crag	53	100	21	0
Chillesford Crag	90	100	10	3
Norwich Crag	112	100	11	9
Newer Red Crag	199	100	10	18
Older Red Crag	148	100	2	22
Coralline Crag	420	100	0·5 (0)	41

This table shows that a sudden influx of arctic shells occurred twice, once in the Newer Red Crag, and again in the Weybourne Crag. It is probable, therefore, that two cold phases occurred during the deposition of the East Anglian Crags. Since the Cromer Forest Bed has a temperate land fauna, it appears that the two cold phases of the Crags were separated from the North Sea Drift by an interglacial.

THE LATER GLACIAL PHASES OF EAST ANGLIA; HUNSTANTON BOULDER-CLAY.—The sequence of climatic phases which followed the glaciation of the Great Chalky Boulder-Clay cannot be established reliably in East Anglia. There is conclusive evidence for one further glaciation, that of the brown Hunstanton Boulder-Clay. This moraine is restricted to the north coast of East Anglia between Hunstanton and Morston, where it is found at a low elevation, reaching 60 ft. O.D. only at Stiffkey. It fills depressions in the earlier members of the succession, and this suggests that a period of erosion (and possibly other events) occurred between the Great Chalky and the Hunstanton Boulder-Clays.

The Hunstanton Boulder-Clay is generally correlated with the Hessle Boulder-Clay of Lincolnshire, and thus included in the "Newer Drift" of Britain.

There are indications, however, that a further glacial phase intervened between the Great Chalky and the Hunstanton Boulder-Clays. Observations which have been interpreted in this sense fall into two groups, (*a*) those relating to the area of the Cromer Ridge, and (*b*) those relating to an "Upper Chalky Boulder-Clay."

THE CROMER RIDGE.—Superimposed on the Great Chalky Boulder-Clay deposits at Cromer, a conspicuous zone of hilly country extends for 20 miles east and west of Cromer, the famous "Cromer Ridge." It is regarded as a terminal moraine, and its structure corroborates this view. The northern slope of the Ridge is steep and passes down into a comparatively even surface (most of which, however, has been destroyed by the sea). This is the flat cliff-top on which Cromer, Runton and Sheringham lie. The north side thus presents the concavity in which the ice lay. The Ridge itself is built up chiefly of violently contorted gravels and some boulder-clay, all of which, having suffered from ice-pressure, are older than the ice-advance which produced the ridge. A second set of gravels is uncontorted and spreads from the ridge southwards (Solomon's "L. 11"). These appear to be the outwash gravels of the Cromer Ridge stage. The eskers at Blakeney and Morston may be mentioned to complete the picture, which, indeed, is

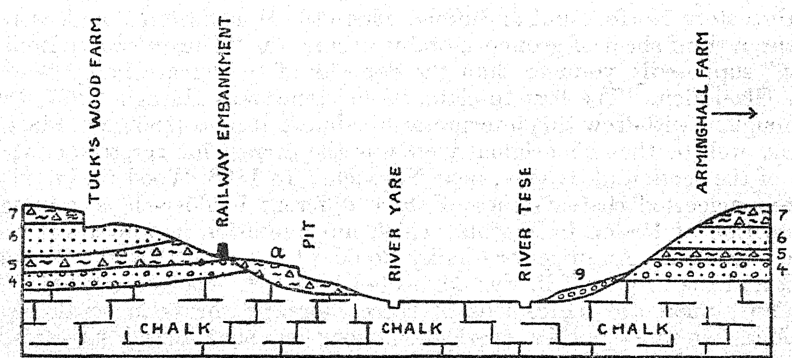


FIG. 34.—Section across the Yare Valley above Norwich. After Harmer, 1867, fig. 2. This type of section has been interpreted either as evidence for three successive ice-transgressions, the boulder clay (*a*) in the valley being taken as an independent third sheet, or as proving only two transgressions, (*a*) being the valley equivalent of the upper boulder clay (7).
(4) Sands with pebble beds (? Crag).
(5) Lower boulder clay.
(6) Midglacial Sands.
(7) Upper boulder clay.
(9) Valley gravel.
(*a*) "Third" boulder clay in the valley.

that of a remarkably fresh glacial landscape. In north Germany, a feature of this kind would be assigned without hesitation to the Weichsel Glaciation, on account of its freshness. The possibility, therefore, has to be considered that the Cromer Ridge is the terminal moraine of the Hunstanton Boulder-Clay glaciation. This boulder-clay lies entirely within the Ridge area and at a lower level so that, topographically, the arrangement complies with a radial cross-section through the marginal deposits of an ice-sheet.

Two geological arguments have been put forward against this chronological identification of the Cromer Ridge with the Hunstanton Boulder-Clay. The first is the petrological one that the erratics of the Cromer Ridge Gravels and the Hunstanton Boulder-Clay are quite different (Solomon, 1932, p. 251), as are the heavy minerals (Solomon, 1932, pp. 261, 262). This

indicates different sources. The second is that at Morston, at a height of not more than 20 feet above the present sea-level (the base of the Cromer Ridge is about 50 ft. O.D.), a shingle bar or beach is covered by Hunstanton Boulder-Clay. This would prove that erosion and a marine phase intervened between the Cromer Ridge and the Hunstanton Boulder-Clay (Solomon, 1932).

If one regards these two arguments as proof of the separation of the two phases, one has to accept a glacial phase, or glaciation, intervening between the Great Chalky-Boulder Clay and the Hunstanton Boulder-Clay. It is called by Solomon "Little Eastern" Glaciation and is restricted to the Cromer Ridge area, as far as the evidence produced by Solomon goes.

THE UPPER CHALKY BOULDER-CLAY.—A different line of argument in favour of a glaciation of the position assigned to the Little Eastern by Solomon is based on the succession of boulder-clays. It is claimed that in south-eastern Norfolk and in Suffolk, where the Hunstanton Boulder-Clay is absent, a third sheet of ground-moraine occurs, the "Upper Chalky Boulder-Clay," supposedly younger than the deposits of the Great Chalky Boulder-Clay Glaciation. The first to claim its existence was Harmer (1867, 1869). Although he withdrew this interpretation almost at once (1869, pp. 448, 449), it may well be that his original view was the correct interpretation, at any rate of the section at Trowse, near Norwich. In 1868, Wood (in Wood and Rome) suggested the existence of three different boulder-clays, relying on the section at Hedon in Norfolk, which interpretation he appears never to have retracted. An upper or Chalky Boulder-Clay, later than the Contorted Drift and the Cromer Till, was advocated by H. B. Woodward (1885).

Thus, there are indications of three morainic sheets in south-eastern Norfolk. It must not be overlooked, however, that actual superposition of three boulder-clays in one section has not yet been found, and that many localities showing the "Upper Chalky Boulder-Clay" at the bottom of a valley can be interpreted by assuming that the second boulder-clay descended into the valley (Fig. 34).

In Suffolk the position is somewhat different. Only two sheets of boulder-clay, or their equivalents, have been observed here, but on the ground of their appearance and lithology, they are generally believed to be the second and third of the south-east Norfolk sheets just mentioned.

In 1914 Boswell described two sections from Stowmarket showing apparently glacial disturbances of the brickearth overlying the Great Chalky Boulder-Clay. In 1920 Reid Moir suggested that there appeared to be two Chalky boulder-clays in the Ipswich district, and since then Boswell has stated that there is an Upper Chalky Boulder-Clay "stratigraphically as well as lithologically distinct from the Chalky-Jurassic (*i.e.* Great Chalky) Boulder-Clay" (Boswell, 1931, p. 97). The ice of the Upper Chalky Boulder-Clay glaciation would thus have extended south to Hoxne, Stowmarket and Ipswich.

The presence of deposits of two independent glaciers in the Ipswich area has been substantiated by McClintock (1933, p. 1049). He found that "a mature soil profile" separated beds of glacial outwash from overlying boulder-clay in Bolton's Pit, so that a time of temperate climate appears to have intervened between the two.

It is clear that if this Upper Chalky Boulder-Clay represents a glacial

phase later than the Great Chalky Boulder-Clay, it must still antedate Solomon's Little Eastern phase, since the latter terminates with outwash gravel along the Cromer Ridge, far north of the area of Boswell's Upper Chalky Boulder-Clay (see Solomon, 1932, fig. 23). Two alternative explanations suggest themselves. If the Cromer Ridge phase be regarded as a retreat stage of the supposed Upper Chalky Boulder-Clay Glaciation, the two may be considered as one major glacial episode. The evidence nowhere contradicts this interpretation. Thus, there is a serious possibility that at least one more glacial period occurred between the Great Chalky and Hunstanton Boulder-Clays.

Equivalence of Boulder-Clays in Norfolk and Suffolk.—On the other hand, no section is known with all three ground moraines (North Sea, Great Chalky and Upper Chalky) in superposition, but many sections exhibit two. Now the correlation of the Suffolk sections with their two boulder-clays with those in Norfolk has been based on the blue colour and Jurassic

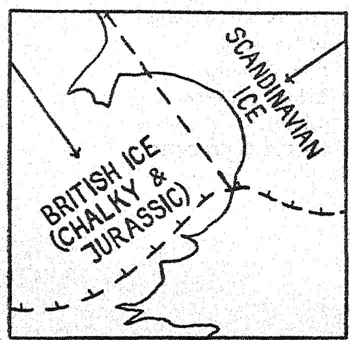


Fig. 35.

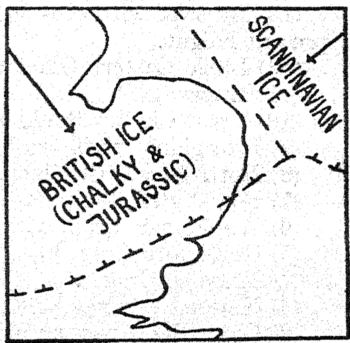


Fig. 36.

Figs. 35, 36.—Suggested interpretation of different boulder clay facies in East Anglia, for the North Sea Drift Glaciation (Fig. 35), and for the Great Chalky Boulder Clay Glaciation (Fig. 36).

contents of the matrix of the lower boulder-clay in Suffolk and the upper boulder-clay in parts of Norfolk, particularly at Corton. But it is quite conceivable that this method of petrological correlation of boulder-clays is unsound (it has been proved repeatedly to be so on the Continent), in view of the great distance of the sections from one another. If this is so, the blue upper boulder-clay at Corton may well be the equivalent of Boswell's white upper boulder-clay of Suffolk, and the blue lower boulder-clay of the Ipswich area the inland equivalent of the North Sea Drift of northeast Norfolk (Figs. 35, 36). This would mean that the two glaciations represented in Suffolk are *the same* as the North Sea Drift and Great Chalky Boulder-Clay Glaciations of Norfolk.

In this case, Solomon's Little Eastern Glaciation might be an independent phase. This is the second alternative interpretation of the Cromer Ridge phase. In either case, however, whether Upper Chalky Boulder-Clay and Cromer Ridge be combined, or the Cromer Ridge left as an independent episode (the Upper Chalky Boulder-Clay being identified with the Great Chalky Boulder-Clay of Norfolk), a glacial episode has to be intercalated

between the Great Chalky and Hunstanton Boulder-Clay Glaciations of Norfolk, to which episode Solomon's term "Little Eastern" is conveniently applied.

It must be admitted, however, that the evidence for the Little Eastern Glaciation does not amount to conclusive proof. As has been said above, it may, after all, have to be merged with the Hunstanton phase in spite of Solomon's arguments. On the other hand, if one combines the two alternatives given above, equating the Upper Chalky Boulder-Clay of Suffolk with the Great Chalky Boulder-Clay of Corton and the Norwich area and regarding the Cromer Ridge as a retreat phase of the glaciation responsible for both, the Little Eastern would again be degraded to an unimportant position in the chronological sequence.

CLIMATIC SUCCESSION OF EAST ANGLIA: SUMMARY.—The succession of climatic phases in East Anglia thus appears to have been as follows:

(14) Hunstanton Boulder-Clay glaciation.
(13) Interval with erosion, and sea-level at about the present height.
(12) Little Eastern Glaciation.
(11) Interval.
} Evidence less conclusive than for other phases. [(13)–(11)]
(10) Great Chalky Boulder-Clay Glaciation.
(9) Interglacial with sea-level higher than at present.
(8) North Sea Drift Glaciation.
(7) Forest Bed, temperate phase.
(6) Weybourne Crag, with cold phase.
(5) Chillesford Crag.
(4) Norwich Crag.
} Temperate. [(5)–(4)]
(3) Newer Red Crag, with cold phase.
(2) Older Red Crag, temperate.
(1) Coralline Crag, temperate or warmer.

It must be noted that this is the minimum of climatic fluctuations that can be recognized, and that certain evidence (Hoxne, for instance), or a different interpretation of the evidence here used, might add further phases to the sequence. At the present state of our knowledge, the glacial part of the succession, from (8) to (14), resembles strikingly the north German sequence of Elster, Saale, Warthe and Weichsel, even in the elusive character of the Warthe phase and the corresponding Little Eastern phase in East Anglia.

MIDLANDS AND NORTH.—Since the sole purpose of the present discussion of the morainic succession of Britain is the establishment of a minimum sequence of climatic events, the interesting work done on the Pleistocene of the Midlands and the North need not be considered. The number of petrologically distinguishable sheets of boulder-clay is greater in the North than in East Anglia, but it is an open question how many glacial phases they represent. Careful mapping with a view to finding weathering horizons and interglacial deposits will settle the issue eventually, and Bisat's work is worthy of special mention in this context. The various attempts at correlating the North with East Anglia, however, are not more than working hypotheses (for instance, Harrison, 1937; Bisat, 1940; Movius, 1942); they have not as yet contributed reliable additions to the sequence of phases established in East Anglia.

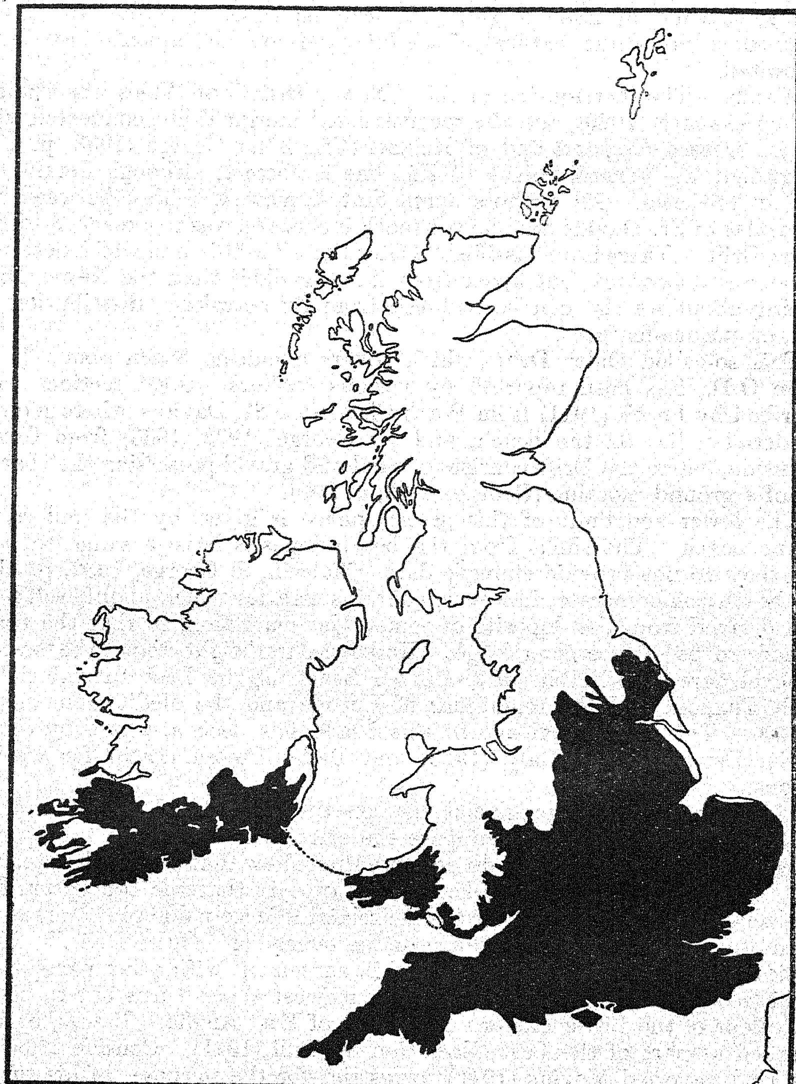


FIG. 37.—The margin of the Newer Drift, according to Charlesworth (1929), reproduced by permission of the Geological Society of London. Probably second phase of the Last Glaciation.

Similarly, the exceedingly important work done by Sandford (1924, 1925, 1929, 1932), Tomlinson (1929, 1935, 1940) and Wills (1937) in the Midlands does not suggest the existence of a greater number of phases than that established in East Anglia. We can pass on, therefore, to Wales, where some important features of the later part of the sequence have been elaborated.

WALES.—The distribution of the "Newer Drift" of Wales was studied by Charlesworth (1929), and the reconstructed marginal line connected with that of eastern England and of Ireland (Fig. 37). George (1933, p. 208) agrees that the general course of this line is correct, although details are open to criticism. All authors agree that southwest Wales, between the peninsulas of St. Davids and Gower (both inclusive), was not reached by the Newer Drift. There is unclassified "Older Drift" in this area which descends to the raised beaches, but apart from it being older than the Newer Drift nothing about its age can be deduced from its petrology, distribution on land, or surface-features.

This so-called Older Drift, which covers a marine beach about 25 ft. above O.D., has been reported by various authors. Good sections were described by Leach (1911) from Porth Clais, near St. David's, where genuine boulder-clay lies on the beach, and by George (1932, 1933) from Gower Peninsula, where the Drift consists of sand and gravel possessing the characters of a ground moraine (George, 1933, p. 209).

The lower age limit of this glacial phase is given by the underlying marine beach. The shells from the beach-deposits have a range so wide that they do not provide climatic data (Chatwin, in George, 1932, p. 317). The beach conglomerate, however, contains erratics which might well have been derived from the deposits of some older glaciation, so that the beach appears to be of interglacial age. Moreover, its height above the present sea-level agrees with that of the lower beach of the Last Interglacial in south England and the remainder of Europe and the Mediterranean (see p. 239). The interglacial age of this beach has been accepted by Geikie (1881), Dewey (1913), Daly (1925) and Baden-Powell (1933) for various reasons.

The defenders of a preglacial age, on the other hand, like Lamplugh (1913), Wright (1914, 1937), suppose the erratics to have been transported by icebergs, and can, even so, do no more than show that the beach antedates the "Older Drift" which overlies it. It appears that the conception of a preglacial age for this beach here as in Ireland is largely due to the unproven assumption of the considerable age of the overlying "Older Drift." If we consider the beach as Last Interglacial in agreement with other parts of the world (see p. 249), the Older Drift of southwest Wales turns out to be the equivalent of the Little Eastern Glaciation of East Anglia. It was, in fact, regarded as part of the Last Glaciation by Bull (1941). Considerations of this kind have led Movius (1942) to restrict for the purposes of his survey the term "Older Drift," altogether to the equivalents of the Little Eastern Glaciation. Considering that the term is generally used to designate undated drift older than the Newer Drift, it appears advisable to continue using it in the old sense, notwithstanding the fact that it includes deposits both antedating and postdating the Last Interglacial.

The Welsh evidence is significant, because it suggests that an Older

Drift glaciation occurred after the Last Interglacial. The parallel afforded by the Warthe Glaciation of north Germany is striking, and the Little Eastern Glaciation is substantiated by this evidence.

IRELAND.—Passing still further to the west, to the south coast of Ireland, we find Wright (1937, p. 117) describing the situation as follows: A 25 ft.-beach extends along the Irish coast, and "from Carnsore Point to Cape Clear at intervals all along the coast are sections reproducing every essential detail of those of Gower." Wright further emphasizes that in "the south of Ireland we are completely within the glaciated region, the ice having passed right out to sea all along the south and west coast." Boulder-clay is actually found, for instance, on the beach at Courtmacsherry Bay, Co. Cork (Wright, 1937, fig. 44). Far-travelled erratics are found in the beach-conglomerate itself (Wright, 1937, p. 118) and, though this author explains them at some length as transported by floating ice, he admits (p. 119) that "a preceding glaciation would perfectly well explain the distribution of erratics which is essentially the same as that of the overlying drift."

This is precisely the same arrangement as at Gower. If, therefore, the assumption is correct that the 25 ft. beach of Gower, of Pembrokeshire and of southern Ireland is the same as that of north Devon, the south coast of England and many other places in Europe, *i.e.* the beach formed during a phase of high sea-level of the Last Interglacial, Ireland must have been completely glaciated during some phase of the Last Glaciation.

A later and smaller phase of the Last Glaciation is indicated by the terminal moraine traced by Charlesworth (1928, 1929; also Wright, 1937, fig. 39), which runs from Co. Clare across the mouth of the Shannon eastwards, round the north of the Wicklow Mountains, then south along the Irish east coast. He picks it up again in South Wales, connects it with the York moraines and draws it south along the English east coast to the Wash, where it links up naturally with the Hunstanton Boulder-Clay deposits. This is the southern limit of the "Newer Drift," which we have reason to suspect of representing the second phase of the Last Glaciation in East Anglia.

The above terminal moraine, however, does not, in Wright's view, represent the last phase of the Last Glaciation. He bases his conclusion on the same criterion of the distribution of unsilted lakes, which has been applied with success in north Germany and Poland in order to separate the Pomeranian stage from the Weichsel stage; for he finds (Wright, 1937, p. 97) that there are no open lakes anywhere near the margin of the Newer Drift in the British Isles. "In Great Britain they are confined to hilly regions, such as the Highlands of Scotland, the western Southern Uplands, and the Lake District of Cumberland and Westmorland. In Ireland innumerable lakes cover the whole country to the northwest of a line from County Down to the mouth of the Shannon, but do not extend outward to the margin of the Newer Drift as traced by Charlesworth." (See also Wright, 1939, pp. 28–31, fig. 19.) It appears, therefore, that the last stage of the Last Glaciation is restricted to the mountain regions just circumscribed, and we thus return to Geikie's old conception that the "Scottish Re-advance" is the equivalent of the Pomeranian Phase.

SUMMARY OF MORAINIC CHRONOLOGY.—Thus the minimum succession of cold phases likely to have occurred in Britain comprises three phases

of the Last Glaciation, one very large glaciation, an earlier equally large glaciation and two minor phases in Crag times.

This sequence resembles the north German one closely in the relative sizes of the glacial phases, and in the tripartition of the Last Glaciation. It can be correlated with the German succession by a number of links, namely, (*a*) the two very large glaciations followed by three successively smaller glacial phases, (*b*) only phases 2 and 3 of the Last Glaciation showing fresh glacial topography, and only phase 3 enclosing large numbers of glacial lakes and other unfilled depressions, (*c*) there being beneath the oldest moraine (North Sea Drift or Elster) deposits with a fauna of the Antepenultimate Interglacial (Forest Bed and Tegelen). These coincidences render it probable, though not certain, that the following correlation is correct:

Scottish Re-advance: Pomeranian.
Newer Drift: Weichsel.
Little Eastern: Warthe.
25 ft.-beach: Last Interglacial.
Great Chalky Boulder-Clay: Saale.
Weathering, denudation, high sea-level: Great Interglacial.
North Sea Drift: Elster.
Forest Bed: Tegelen (approximately), Antepenultimate Interglacial.
Two phases in Crag: ? two phases of Günz Glaciation in the Alps.

B. THE THAMES BASIN.

The Thames and the Somme are both trunk-streams with estuaries. It is to be expected, therefore, that eustatic fluctuations of the sea-level are registered in the terraces of the lower Thames as they were found to be in the Somme on the other side of the English Channel. But while the Somme was part of the loess belt during the glacial phases, the Thames was considerably nearer to the ice-sheets and mostly included in the tundra and sander zone. The ice actually reached the edge of the Thames valley at least once. Solifluction deposits abound, and loessic deposits are rare.

Age of the Boyn Hill Terrace.—The best-known terrace of the Thames is the High Terrace, Boyn Hill or 100 ft. Terrace. It is preserved well enough for the reconstruction of the river's gradient at the time when the aggradation of the gravels came to an end, and the longitudinal profile obtained provides the most important chronological link with the Continent. As its name implies, the surface of the highest fluviatile deposits of this terrace maintains a constant height of almost exactly 100 ft. above the present floodplain, from Taplow near Maidenhead to Swanscombe near Gravesend, a distance of about 50 miles. For the last 13 miles, from the mouth of the Lea to Swanscombe, the gradient has become less than 3 in. per mile. This is so little that the sea cannot have been far.

The modern floodplain is estuarine between the mouth of the Lea and Swanscombe; its gradient is zero, and its surface outside the river walls lies at about 7 ft. O.D. The gradient of about 3 in. per mile is observed in the modern floodplain about 15 miles *upstream* of the stretch where it occurs in the Boyn Hill Terrace. From this it may be inferred that the horizontal section of the estuary was hardly more than 15 miles downstream

from Swanscombe. Although this estimate is somewhat conjectural, being based on levels which can vary locally within a few feet, the use of alternative values does not produce a radically different result. It is safe to conclude, therefore, that Swanscombe lay some miles upstream of the neck of the estuary in Boyn Hill Terrace times.

The surface of the terrace may, though need not, have sloped another 3 ft. in these 15 miles, and even if so the highwater mark referable to the surface of the Boyn Hill Terrace aggradation would have been near 107 ft. O.D., or 32 m. *This is the highwater level of the Tyrrhenian sea-level of the Great Interglacial*, as established for the Coasts of the English Channel, the Mediterranean and other parts of the world (see Chapter IX, p. 249).

The top of the fluviatile aggradation of the Boyn Hill Terrace, therefore, is dated as contemporary with the 32 m. sea-level of the Great Interglacial. This chronological position is corroborated in various ways.

Sequence of High Sea-levels of the Thames Basin.—First, the two aggradation phases which succeeded the Boyn Hill Terrace, *i.e.* the Taplow and Upper Floodplain stages, attained to levels of about 60 ft. and 25 ft. and are, therefore, referable to the Main and Late Monastirian sea-levels of 18 and 7.5 metres. This will be substantiated further on. Above the Boyn Hill Terrace level of 100 ft. a 200 ft. platform was established and correlated with the Milazzian (60 m.) sea-level by Wooldridge (1928). Two still higher levels have been found by Wooldridge (1927*b*), the 400 ft. level of the Pebble Gravel, and the so-called Diestian level of 540 to possibly as much as 700 ft. (called the "600 ft. level"). Judging merely by their altitude, these might correspond to the Sicilian and Calabrian levels of the Mediterranean, the former of which is found at the mouth of the Somme also, at a height of 103 m. The succession of the sea-levels will be discussed in some detail in Chapter IX. It is, however, clear from the few figures given here that the phases of high sea-level recognizable in the Thames Basin agree with those found elsewhere, and that the entire sequence, namely Calabrian, Sicilian, Milazzian, Tyrrhenian, Main and Late Monastirian, can apparently be identified. For the three higher ones only altimetric evidence is available, whilst the three lower ones are confirmed palaeontologically, and geologically by their relation to glacial phases.

Fauna Proving Great Interglacial Age of the Boyn Hill Terrace.—The Great Interglacial age of the Boyn Hill Terrace is further confirmed by its contained fossils. At Swanscombe, near Gravesend, Kent, the aggradation consists of a Lower Gravel and a Middle Gravel separated by a partially weathered loam. The faunas of these two gravels are given in Chapter X (pp. 263, 264). Both indicate an age later than the Antepenultimate Interglacial and earlier than the Last Interglacial. The fallow deer, for instance, appears as *Dama clactonianus*, whilst the Antepenultimate Interglacial contains *D. savini* the Last Interglacial a form of *D. dama*, the three constituting, as far as one can see, a phylogenetic lineage. The Lower Gravel contains, as a survival from Antepenultimate Interglacial times, *Trogontherium cuvieri*, provided this find is correctly referred to this bed.* From the Middle Gravel two teeth of an early form of *Elephas primigenius* have been reported (King and Oakley, 1936). Such early *E. primigenius*

* Not found in Swanscombe but at Ingress Vale (Stopes, 1904, p. 804). This was first pointed out by Oakley in the Swanscombe Report, p. 57.

or late *E. trogontherii*, characterize on the Continent the time around the Penultimate Glaciation. Their fauna being temperate, if not slightly warmer than to-day (see Mollusca, p. 270), both the Lower and Middle Gravels of Swanscombe, therefore, are likely to date from the Penultimate or Great Interglacial.

ARCHÆOLOGY OF BOYN HILL TERRACE.—The Great Interglacial age of the aggradation of the Boyn Hill Terrace is thus confirmed on two entirely independent lines. The third line of approach, the archæological one, has been deliberately omitted as a method of dating in the present context. It is worth mentioning, however, that the Clactonian II of the Lower Gravel, and the Middle Acheulian of the Middle Gravel, agree with the date determined on a geological and palaeontological basis. Hawkes, in co-operation with Oakley and Warren, considered the chronological aspect of the Swanscombe industries in great detail (Swanscombe Report, 1938).

BOYN HILL TERRACE AS DATUM LINE.—The Boyn Hill Terrace, more precisely the surface of the fluviatile aggradation of this terrace as observed in the Lower Thames valley at Swanscombe (Barnfield Pit), at 110 ft. O.D., may for these reasons be taken as the "datum line" for the Pleistocene chronology of the Thames Basin. No doubt this terrace is eminently suitable for this purpose, since the Pleistocene deposits between Reading and the Estuary can readily be compared with the Boyn Hill level everywhere. Wooldridge (1928, p. 3) has stressed this point before.

All climatic events in the Thames Basin can thus be divided into those which occurred previous to the Tyrrhenian 32 m. sea-level and those which happened thereafter.

LOWER AND MIDDLE PLEISTOCENE SUCCESSION LEADING UP TO THE TYRRHENIAN SEA-LEVEL.—The Pleistocene succession of the Thames Basin is exceedingly complex, and difficult to condense into a few paragraphs. It is advisable not to follow the logical course of tracing events from our datum line backwards into the past, but rather to describe them in their proper chronological order, beginning with the suspected Pliocene phases and descending to the Boyn Hill Terrace.

The complexity of the Thames Pleistocene is not only chronological but also local. The Thames changed its course during the Pleistocene. It flowed originally through the Vale of St. Albans (Sherlock, 1924) north of London, and at a later date through gaps near Watford, past Harrow and Finchley (Fig. 38). These northern and intermediate courses meet at Ware, north-east of London, whence the river either went north through the Stevenage Gap into the Wash (Sherlock's view, 1924, p. 25), or east through Essex into the Blackwater (Wooldridge's view, 1938, p. 658). The third route taken by the Thames is the present, southernmost, one. Fortunately the river occupied its present valley between Reading and the mouth of the Colne continuously while these changes were taking place, so that the succession of terraces and gravel trains can be substantiated there. The most important area is that between Bourne End near Maidenhead and the lower Colne. In the following paragraphs the local development will be neglected, except for certain crucial points, in order to work out more clearly the climatic sequence of events. Readers interested in the details will find them in a series of admirable papers published by Wooldridge (1927, 1928, 1938).

A further complication which has to be constantly kept in mind is that, as in the Somme (p. 97), so in the Thames the upper part of the course was subject to the climatic rhythm of interglacial erosion and cold-climatic aggradation, whilst the lower course was subject to the eustatic rhythm of interglacial aggradation to a high sea-level and erosion to a low sea-level during the cold phases. The two regimes overlap in the area now covered by Greater London, which makes the distinction fairly simple in practice, but it must be noted that the junction was sometimes higher upstream, sometimes farther downstream. At present the junction (under natural conditions) lies a few miles upstream from Teddington; during the Antepenultimate Glaciation it shifted, though quite temporarily, downstream, presumably to beyond Gravesend.

THE 660 FT. AND 400 FT. LEVELS.—The earliest recognizable phases are two platforms studied by Wooldridge (1927*b*), at about 600 ft. and 400 ft. O.D. The former appears to have experienced slight warping after its formation, but the 400 ft. level is undisturbed.

The 600 ft. level is that of the Lenham Beds of Diestian age (*i.e.* Pliocene and older than the Coralline Crag); it is essentially marine. The 400 ft. level, that of the Pebble Gravel, is essentially fluviatile, as Wooldridge has shown by means of the horizontal distribution of the gravel constituents (1927*b*, p. 116, fig. 13). These two platforms can be regarded tentatively as the equivalents of the Calabrian and the Sicilian phases of the Mediterranean.

At the end of the Pebble Gravel phase, therefore, the rivers then occupying the Thames area were graded to a sea-level of somewhat below 400 ft. Tributaries brought Lower Greensand chert across the line of the present Thames Valley, and the main drainage line, *i.e.* the ancestral Thames, ran north-east along the pre-Vale of St. Albans.

STAGES BETWEEN THE 400 FT. AND 200 FT. LEVELS: OLDER DRIFT.—The phase immediately following the formation of the 400 ft. platform is that of the Older Drift of Wooldridge (1938, p. 645), which is essentially the same as the Pebbly Clay and Sand, plus Clay with Flints, of Sherlock (1924). These deposits are regarded by all who have studied them as products of a cold climate, either as a great sheet of solifluction deposits, or even as the moraine of a local glaciation of the Chiltern Hills (Barrow, 1918, 1919). The latter interpretation is less probable, because of the low elevation of the Chiltern (up to 800 ft.), but this point is an unimportant detail.

In the area between Maidenhead and the Colne, the Older Drift is generally confined to levels above 400 ft. In the triangle between Chalfont St. Giles, Amersham and Chenies it rests on a level bench of almost exactly 400 ft. There is no evidence here of down-cutting having taken place following the Pebble Gravel phase and preceding the Older Drift. About one mile north and north-west of Beaconsfield Station, however, the Older Drift is shown on the One-inch Geological Map to descend to 350 and 330 ft. Whether this is due to later solifluction, or evidence for a down-cutting which preceded the formation of the Older Drift, cannot be ascertained.

BENCH OF HIGHER GRAVEL TRAIN.—It has to be assumed that during a cold phase as that of the Older Drift, the sea-level was lowered, and one is tempted to regard the down-cutting to the first bench below the 400 ft. level, *i.e.* that of the Higher Gravel Train, as the response to this low sea-level.

If this is so, the Older Drift and the cutting of this bench are contemporaneous. This would explain the low position of the Older Drift north of Beaconsfield Station, and we need not admit more than one cold phase.

Alternatively, if we regard the bench as later than the Older Drift, we are compelled to assume two separate cold phases. The gradient of the bench of the Higher Gravel Train (6 ft. per mile) appears to be too steep for a sizable river in a mild climate. The bench drops from 320 ft. north of Beaconsfield to 290 ft. at Heronsgate near Rickmansworth. Such steep gradient suggests an ungraded river in a cold climate.

Our aim being the establishment of the *minimum* number of climatic phases, only one cold phase is here assumed to comprise both the Older Drift and the cutting of the bench of the Higher Gravel Train.

Surface of Higher Gravel Train.—At the conclusion of this phase one finds that the bench was covered with a sheet of gravel which, according to Wooldridge, drops from over 350 ft. near Beaconsfield to 280 ft. near Rickmansworth, or about 7 ft. per mile. This gradient again is suggestive of an ungraded river, presumably of a cold climate. However that may be, the direction of the drainage was, by that time, no longer through the Vale of St. Albans, but through gaps south of Watford and eastwards through the Finchley depression to Ware. Wooldridge (1938) has, with much ingenuity, established this state of affairs.

Lower Gravel Train.—The next recognizable phase is that of the Lower Gravel Train. Its gravels are separated from the Higher Gravel Train by a "rise"; their surface is at about 306 ft. south of Beaconsfield, and 290 ft. near the Colne valley (Wooldridge, 1938, p. 638). The bench is certainly lower than that of the Higher Gravel Train, but higher than that of the succeeding 200 ft. stage. According to Wooldridge, the Lower Gravel Train takes a course slightly different from that of the Higher Gravel Train west of the Colne valley. This appears to confirm its independent nature.

It is difficult to say whether the cutting of the bench of the Lower Gravel Train indicates another phase of low sea-level and, therefore, a glacial phase. Had the river continued to follow its older course, this interpretation would have to be accepted. The southward shift of the Lower Gravel Train east of the Colne (the Harefield Gravels), however, suggests a shortening of the course of the river, compared with the Higher Gravel Train. This must have sent a knickpoint upstream, which might account for the bench of the Lower Gravel Train.

The stages of river-development discussed so far suggest that at least one cold phase intervened, and possibly as many as three.

The 200. ft. Platform.—Wooldridge (1927*a*, p. 257; 1928; Saner and Wooldridge, 1929) has brought forward a considerable amount of evidence for a platform at about 200 ft. O.D., which he correlated with the Milazzian sea-level. Vast tracts of the eastern portion of the Thames Basin appear to have been denuded to about 200 ft., since the boulder-clay rests on a platform of this height in most of western Essex (the Ambersham Terrace of Green, 1936; Bull, 1941). This suggests a phase of considerable duration. The grading of the rivers to this base-level must have attained great proportions, since benches of 200 ft. or slightly over are found as far west as the area of Gerrard's Cross. The Finchley Depression also can be referred to

this level, since its sub-drift surface at Church End, Finchley, is at 224 ft. O.D. (Wooldridge, 1938, p. 643), and the entire "lip" of the sub-drift surface along the south-western edge of the Finchley boulder-clay is near 200 ft. O.D.

If one attempts to continue this level up the Thames valley towards Maidenhead it becomes obvious that the 210 ft. bench of the area round Hollybush Farm, two miles south-east of Gerrard's Cross, with its cap of gravel, merges into the gravel train which Wooldridge called the Winter-Hill Terrace.

The Winter-Hill Terrace, *sensu stricto*, however, has a greater gradient and its surface is, near Iver and Hillingdon, on either side of the Colne, not higher than 200 and 188 ft. respectively, with a bench considerably below these figures. It is apparent, therefore, that two levels merge as one goes upstream since, near the Colne valley, there is one with the bench at 210 ft. or more and another with the aggradation surface at 200 ft. or less. The former will henceforth be called the "Finchley Leaf" and the latter the "Kingston Leaf," for reasons to be given below.

In the Burnham Beeches area there is only one identifiable level at a suitable height, viz. bench at 220 ft. with gravel up to 250 ft.

It is probable, therefore, that the bench of the Winter-Hill Terrace from Burnham Beeches upstream, and conceivably some of its gravel, are of the age of the 200 ft. platform, when the Thames flowed through the Finchley depression into the Milazzian Sea.

THE KINGSTON LEAF BENCH.—The first recognizable event following the 200 ft. platform and the Finchley Leaf is the cutting of the Kingston Leaf bench below Burnham Beeches, where it drops steeply from 220 ft. (Burnham Beeches) to less than 180 ft. at Hillingdon. Thence it can be continued into the bench of the Kingston and Richmond Hill gravels, 13 miles distant, at about 150 ft. O.D., or somewhat less. This bench cannot be carried through the Finchley Depression, the lip of which lies at 200 ft., and affords no gap or channel of lower height for the river to pass through. During the Kingston Leaf bench-stage, therefore, the river had abandoned the course past Finchley to Ware. Instead, it took the route followed by the modern Thames, through the gap between Hampstead Heath and the North Downs.

The gradient of the Kingston Leaf bench is remarkably steep, 3·5 ft. per mile. As it appears to diverge from the almost horizontal floor of the 200 ft. level at Burnham Beeches, it is suggested that the point of divergence is a knickpoint up to which retrogressive erosion had cut back from a low sea-level. The downstream continuation beyond Richmond of the Kingston Leaf bench at a slightly decreased gradient (2 ft. per mile) takes us across a gap of 25 miles to the gravels of Dartford Heath. This connection was suggested by Hinton and Kennard (1905, p. 80).

The distances involved are admittedly large and the connections correspondingly hypothetical. They appear more trustworthy, however, if one considers that the three bench-fragments in question, at Hillingdon, Kingston and Richmond Hill, and Dartford Heath, with their covering gravels, are all unquestionably younger than the 200 ft. platform and the Finchley Leaf and, as will be seen, older than the Boyn Hill Terrace. Their chronological position, therefore, is hemmed in between two successive phases of

high sea-level and in view of the fact that they present a gradient which one would expect in a valley cutting down to a low sea-level they can be regarded, at least, as almost contemporaneous.

The argument of the preceding paragraph may, perhaps, be challenged by some with respect to Dartford Heath. As early as 1905 Hinton and Kennard regarded the Dartford Heath gravel as resting on a higher bench than that of the Swanscombe gravel, and H. B. Woodward (1909) followed them. Chandler and Leach (1912), however, came to the conclusion that the levels did not support the separation, and they regarded the Swanscombe bench (then thought to be at 90 ft. O.D., gravels up to 115 ft. O.D.) as the equivalent of that at Dartford (from 90 or 100 ft. O.D. with gravels up to 120 or 130 ft. O.D.). Dartford is about 5 miles upstream from Swanscombe. The difference appeared to be due to the natural gradient of the river. But Dines, King and Oakley (1938, in Swanscombe Report, pp. 23–27) have since found that the fluviatile deposits at Swanscombe extend from 75 to 110 ft. O.D. The gradients would thus be between 3 to 5 ft. per mile for the bench, and 2 to 4 ft. per mile for the surface. Such a surface gradient is, however, too high for the Boyn Hill Terrace, and the gradient of the bench also would be steeper than any other known in this part of the river. In view of the new figures, therefore, it is at least conceivable that both bench and gravel surface at Dartford Heath* represent a somewhat earlier stage than the fluviatile part of the Swanscombe (Barnfield Pit) section.

We thus return to Hinton and Kennard's view of nearly 40 years ago, and are led to admit that, in the area of Swanscombe, Dartford, Grays, etc., there is a bench at approximately 90 to 100 ft., and another at 75 ft. O.D., the former conceivably being the continuation of the Kingston Leaf bench, the latter the true Boyn Hill bench. The gravels on the former would attain to 130 ft., those on the latter to 110 ft. O.D. Even if these differences be regarded as too small to be significant, the bench of the Kingston Leaf at Richmond, which is 30–40 ft. above the local Boyn Hill bench, makes the existence of an independent Kingston Leaf stage probable.

Age of Kingston Leaf and Boyn Hill Benches Relative to the Thames Valley Glaciation.—Now both the Kingston Leaf and Boyn Hill benches are older than the ice which reached the Thames valley. Beginning with the lower, Boyn Hill, bench, this is overlain by true boulder-clay at Hornchurch, opposite Dartford, at slightly under 80 ft. O.D., the boulder-clay in turn being covered by river gravel up to about 107 ft. O.D. The Boyn Hill bench in this part of the river, therefore, is older than the Thames Valley glaciation, but it appears to have been cut immediately prior to the arrival of the ice, since the boulder-clay lies directly on the bench.

The Kingston Leaf bench, therefore, also must antedate this glaciation. This is borne out by the abundant evidence brought forward by Wooldridge (1927*a*) and Saner and Wooldridge (1929) for the cutting of valleys into the 200 ft. platform prior to the arrival of the ice in Essex. It is thus possible

* It is possible that the gravels of Dartford Heath are composite, consisting of a gravel resting on a bench at about 100 ft., and a lower one which may be a genuine Boyn Hill deposit. The term "Dartford Heath gravels" is here restricted to the higher deposit.

to add the important detail that *two* phases of downcutting intervened between the 200 ft. platform and the arrival of the ice, corresponding to two low sea-levels and thus to two cold phases. The second of these appears to have been contemporaneous with the glaciation, as shown by the Hornchurch section.

KINGSTON LEAF GRAVEL.—The aggradation of gravel which rests on the "Winter Hill" bench between Burnham Beeches and the Colne is considered by Saner and Wooldridge (1929, p. 249) as connected with that of Richmond and Kingston Hill. The gravel of the latter locality is stated to be of the "Winter Hill type containing Bunter quartzite," and these authors conclude that "its constitution and elevation links it with the Winter Hill terrace." Later on, Wooldridge (1938, p. 643) added evidence for the glacial outwash from the ice-lobes at Aldenham and Finchley merging with these gravels. From this it may be inferred that a cold-climatic aggradation overwhelmed the Kingston Leaf bench during the Thames Valley glaciation. This aggradation was up to 30 ft. thick at Richmond, Kingston and Wimbledon.

GLACIATION AND DISPLACEMENT OF THE THAMES.—Following Sherlock and Wooldridge, the view is now generally held that the advance of the ice caused the southward shift of the Thames. That these two events were nearly contemporaneous is apparent from the evidence. The displacement was, however, not so simple a process as one is inclined to visualize. When the ice arrived at Aldenham and Finchley and began to shed meltwater down the present Colne and Brent, the Kingston Leaf bench along the present Thames valley had been cut, and the Thames was flowing along its present course. The displacement may have been caused by the plugging with ice of the old Thames valley, for instance, near Ware, so that some time was available for the cutting of the new (Kingston Leaf) bench through the London gap. The width of the Kingston Leaf bench at Kingston, Richmond and Wimbledon suggests that the new valley was not a narrow gorge, and one is inclined to allot more time to the formation of this bench than the ice is likely to have taken in order to advance from Ware to Finchley. The precise relation of the Thames valley glaciation to the displacement of the Thames, therefore, is worthy of further detailed investigation.

THE BOYN HILL DEPOSITS.—From Boyn Hill times onwards our attention will be concentrated chiefly on the lower part of the Thames valley, downstream from London, where the rhythm of eustatic down-cutting and aggradation agrees, with practically no time lag, with the phases of low and high sea-level and, therefore, of cold and temperate phases. In the upper reaches of the river, knickpoints initiated by a cold phase of low sea-level are found to be cutting back in the succeeding interglacial or even later, and the superposition of climatic aggradation makes conditions exceedingly complex. The object of the present discussion being the establishment of a succession of climatic events, the lower Thames is to be preferred, since the difficulty introduced higher up the valley by the time-lag of erosion can safely be disregarded here.

It is to be assumed that, following the withdrawal of the ice from the scene, downcutting continued in the lower Thames until the sea-level had risen sufficiently for eustatic aggradation to begin. This means that, most probably, sufficient time was available for the removal of glacial deposits,

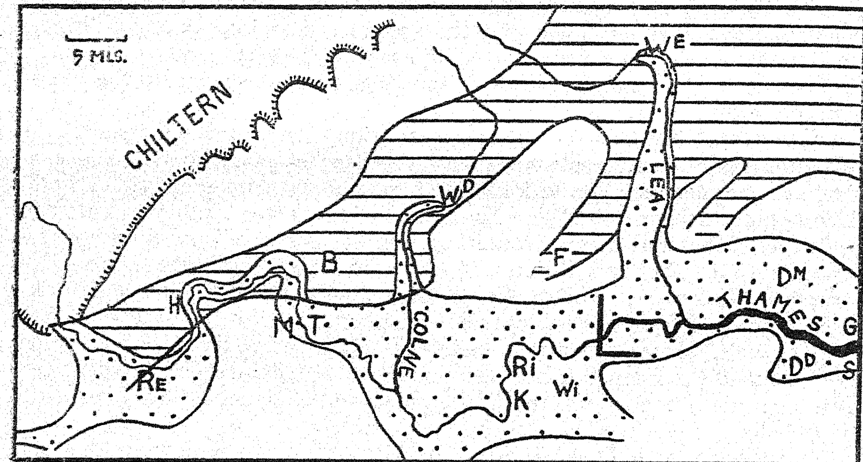


FIG. 38.—The two drift belts of the London Basin, according to Wooldridge (1938, fig. 1, p. 628). Horizontal lines: older drift belt including the glacial drift, largely covering the Thames course prior to the great southward displacement. Dots: Later drift belt, from Boyn Hill stage onwards. (The transitional phase of the Winter Hill gravels above the mouth of the Colne was included by Wooldridge in the Older Drift, but further downstream in the later drift.)

B.	Beaconsfield.	M.	Maidenhead.
Dd.	Dartford.	Re.	Reading.
Dm.	Dagenham.	Ri.	Richmond.
F.	Finchley.	S.	Swanscombe.
G.	Grays.	T.	Taplow.
H.	Henley.	Wd.	Watford.
K.	Kingston.	We.	Ware.
L.	London.	Wi.	Wimbledon.

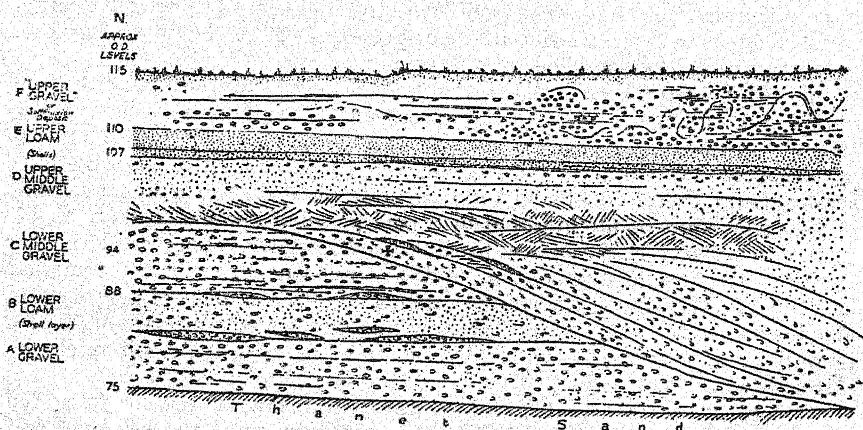


FIG. 39.—The section of Barnfield Pit, Swanscombe, Kent. From Swanscombe Committee Report (1938), by permission of the Royal Anthropological Institute.

meltwater and climatic river gravels which may have covered the Boyn Hill bench, except in protected places, such as Hornchurch. In most places, therefore, the aggradation found resting on the bench testifies to a full interglacial with a temperate climate. This is borne out by the section of Barnfield Pit, Swanscombe, which has been studied for many years and recently received special attention following the discovery of the skull of *Homo* cf. *sapiens* in these deposits (Marston, 1938; Hinton, Oakley, Dines, King, Kennard, Hawkes, Warren, Cotton, Le Gros Clark and Morant, in Swanscombe Committee Report, 1938).

The section (Fig. 39) comprises a Lower and a Middle Gravel separated by a partly weathered loam (Lower Loam) and with a capping of floodloam, the Upper Loam. This concludes the fluviatile deposits. The so-called Upper Gravel is a solifluction deposit of later date (Burchell, 1934*b*) resting on an eroded surface of Upper Loam and Middle Gravel. The temperate climate of the entire fluviatile aggradation is attested by the mammalia and shells of the Lower Gravel (King and Oakley, 1936, p. 56), the shells of the Lower Loam (Kennard, see p. 270), and the mammalia ('Swanscombe Rep.,' p. 28) and the shells (Kennard, in 'Swanscombe Rep.,' p. 28) of the Middle Gravel (see also Chapter X, pp. 263, 269).

Interruption of Swanscombe Aggradation.—The eustatic aggradation of the Boyn Hill deposits below London was not continuous. In the section of Barnfield Pit a break is indicated by the weathering of the Lower Loam. The weathered nature of the upper part of the Lower Loam had been noticed by many observers but, apparently, never been confirmed chemically. For this reason a pH test was carried out, with these results:

	pH.
Gravel just above loam . . .	7·4
Loam band at base of gravel . .	7·4
,, 10 cm. down	7·2
,, 20 ,, ,, ...	7·2
,, 30 ,, ,, ...	7·4
,, 40 ,, ,, ...	8·0
,, 60 ,, ,, ...	8·3
,, 80 ,, ,, ...	8·1
,, 100 ,, ,, ...	8·0

These figures support the contention that the loam was exposed to chemical weathering for some time before the Middle Gravel was deposited on it, though the increase in alkalinity in the overlying Middle Gravel is slight.

Clacton Channel.—K. P. Oakley (1937, p. 253) places in this hiatus the formation of a new, lower, bench, that of the Clacton Channel. It lies at -15 ft. O.D. or lower at Clacton-on-Sea, where the gravel contains a typical fauna of the Swanscombe type (p. 263), and is covered by estuarine deposits indicating the fresh rise of the sea-level which followed the phase of channel-cutting. Looking for a possible equivalent upstream, the deposits at Grays (Little) Thurrock, opposite Swanscombe, north of the Thames, have been considered as such, but they rest on a bench at about zero O.D. (Tylor, 1869), too low to grade into the Clacton deposit unless the latter

extends to a level much lower than that of −15 ft. O.D. at present known. (For fauna of Grays, see p. 263.)

Ilford and Stoke Newington.—Purely altimetrically, the benches of the Ilford deposits, at about 30 ft. O.D. (King and Oakley, 1936, p. 59), and of Stoke Newington, west of the mouth of the Lea (about 50 ft. O.D., estimated from figures given by Smith, 1896), might belong to the required bench. But even at Clacton the bench can, with little difficulty, be interpreted as the continuation of the Barnfield Pit level of 75 ft. O.D. At Ilford the fauna seems to indicate an age later than Grays and Clacton (mammals, Hinton, 1910, p. 493; mollusca, Kennard, 1916, p. 255), and at Stoke Newington the fine grade of the deposits compared with the coarser grade downstream at Swanscombe raises difficulties.

Thus, it is impossible to say with certainty that there was an oscillation with a low sea-level which intervened in the course of the aggradation up to the 100 ft. sea-level. On the other hand, since Grays and Stoke Newington, quite apart from Clacton, are difficult to combine into a single bench, it is possible to hold the view that there were two such phases. This group of localities requires careful study, since it affords a possibility of detecting minor oscillations which have so far been neglected by most authors.

Granting that the existence of benches lower than the Boyn Hill bench, at Ilford and Stoke Newington, and at Grays, suggests low sea-levels previous to the attainment of the 100 ft. sea-level, a view expounded chiefly by King and Oakley (1936), one or two oscillations may have followed the Thames Valley glaciation, before the sea-level had risen to its full interglacial height of 100 ft. O.D.

Thus, we have arrived at our datum-line.

High Sea-Level Phases later than the 100 ft. Sea-Level.—The climatic succession subsequent to the warm interglacial of the 100 ft. Tyrrhenian sea is subdivided by two further stages of high sea-level, at 60 and 25 ft. respectively. These are the Main and Late Monastirian levels. Their identification in the Thames provides two further important datum-lines for this area.

Taplow Terrace and 60 ft. Sea-Level.—The deposits of the Taplow stage constitute a group which follows the Boyn Hill stage. They are often comprised under the term "50 ft. Terrace." Whilst the deposits are too complex to be discussed here, it is comparatively easy to derive altimetrically the height reached by the sea-level at the end of this stage, just before the next major downcutting began which transforned the Taplow deposits into a terrace. The Taplow aggradation is well preserved above London, whilst below London brickearths prevail instead. If one combines the numerous occurrences of Taplow gravels between Bourne End and Taplow near Maidenhead, and Ealing and Richmond, in a longitudinal profile, disregarding the subaerial brickearth which rests on the gravel in many places, one finds that the gravel surface has a gradient of about 2 ft. per mile as far as Feltham, dropping from 106 ft. to 73 ft. O.D. A gradient of about 1 ft. per mile may be discerned between Feltham and Gunnersbury near Ealing, where the surface lies between 70 and 60 ft. O.D. But further downstream, in the area of Hyde Park and Kensington Gardens, and at a few other places, gravel spreads occur at about the same level, suggesting that the surface of the fluviatile deposits of the Taplow Terrace remains at about this height

of 60 to 70 ft. This indicates that the estuary of the river lay at this level, which would agree with the Main Monastirian sea-level observed elsewhere.

ENDSLEIGH GARDENS LEVEL.—It is not quite certain whether the localities near Euston Station ("Endsleigh Gardens," etc., described by Hicks, 1892) belong to the Taplow aggradation. The bench or slightly inclined valley-side, on which they rest, is certainly older than the Taplow bench elsewhere, since it is as high as 60 ft. O.D. (average). Immediately on the London Clay constituting the "bench," in depressions or small tributary valleys, a dark clayey loam occurred which yielded a young "mammoth" and a flora. The latter was determined by Clement Reid; it contains about 20 species. Hicks (1892), and King and Oakley (1936), probably influenced by the alleged cold character of the Taplow Terrace and by the occurrence of the "mammoth" at Endsleigh Gardens, stress that this flora *could* have existed in a climate somewhat cooler than the present. But, although the plants in question might have been able to stand a climate with "a heavy winter snowfall" (King and Oakley, 1936, p. 62), Mr. A. J. Wilmott kindly informs me that this statement has to be supplemented by the qualification that there is no evidence in the list that the climate was different from that of the present time. Climatically, therefore, the Endsleigh Gardens mammoth loam is somewhat nondescript.

Whatever the climatic character of this deposit, the overlying gravels and sands need not have been laid down without a hiatus. Altimetrically these gravels and loamy sands can very well be the transgressing uppermost strata of the Taplow aggradation, since their surface lies between 62 and 70 ft. O.D. The upper stratum of loamy sands is suggestive of estuarine conditions. With them (layer *c* of Hicks) the fluviatile series ceases; it is covered by a solifluction deposit (Hicks's *b*).

A number of other sections can with little difficulty be assigned to the Taplow aggradation, but none appear to provide reliable figures for the maximum altitude reached by the river. Solifluction deposits and made-up ground hide the fluviatile surface in many places, whilst denudation has reduced its height in others.

The evidence available at present thus appears to suggest that the fluviatile aggradation of the Taplow stage mounted up to an estuarine level of between 60 and 70 ft. O.D., corresponding to the Main Monastirian sea-level of 18 m. Nothing reliable is known about the climatic character of *this aggradation*.

UPPER FLOODPLAIN TERRACE AND 25. FT. SEA-LEVEL.—Another phase of high sea-level is suggested by the upper level of the so-called Floodplain Terrace.* The aggradation surface, usually mapped on the official maps as Floodplain Gravel, is from Bourne End downstream to Wraysbury above Windsor parallel to the modern floodplain and about 6 ft. above the latter (gradient about $2\frac{1}{2}$ ft. per mile). About four miles downstream the surface of our terrace is about 8 to 10 ft. above the modern floodplain (Chertsey area), and further downstream the difference increases rapidly, attaining 17 to 20 ft. at Bushy Park near Hampton. This divergence is almost entirely due to the increased gradient of the modern floodplain, especially between Chertsey and Teddington. But below Teddington the modern

* This unfortunate term is retained; a capital letter denotes the Floodplain Terrace of Pleistocene age, a small letter the modern floodplain.

floodplain is practically horizontal, conforming to average highwater. This indicates that the tip of the modern estuary is reached.

It is very interesting to note that the aggradation surface of the Floodplain Terrace continues to drop as far as Bushy Park, where a wide expanse of gravel with numerous superficial exposures presents a seemingly homogeneous surface from 39 ft. O.D. at the valley side to 35 ft. O.D. near the river.

Two miles further downstream, however, at Twickenham and Ham, two aggradation surfaces are discernible, both apparently belonging to the Floodplain Terrace aggradation. They lie at 35 ft. O.D. at Twickenham, and at 26 to 28 ft. O.D. on the Ham side of the river. The difference between the two levels is slight, but it increases to 10 to 12 ft. at Kew and Barnes, and data from Fulham, Chelsea and Westminster suggest that the difference remains the same or even increases slightly further downstream.

This divergence of the Upper and Lower Floodplain Terrace levels is due to a falling away of the Lower level, since the Upper one appears to maintain a constant height of a little over 30 ft. from Twickenham downstream. This is rendered probable by sections like the following:

At Twickenham sewer sections were described by Leeson and Laffan (1894) which show that the surface of the fluviatile aggradation, over a cross-section of the terrace of about half a mile, lies at 35 ft. O.D. $\pm$ 1 ft.

Four miles downstream, at Brentford, near the crossing of the Brentford-Ealing Road with the Great West Road, recent excavations showed fossiliferous deposits with a surface at 32½ ft. O.D., resting on London Clay at 12 ft. O.D. Except for the basal layer, which was coarse, this aggradation consisted of sandy gravel and gravelly sands capped by stratified brown and greyish sands which could well be estuarine. Its fauna (p. 266) consists of temperate elements, including *Elephas antiquus* and *Hippopotamus*.

The City of London flat, between the mouths of the Fleet and the Lea, from St. Paul's to Stepney and Victoria Park, belongs altimetrically to the Upper Floodplain aggradation. On the 6-inch map of the Geological Survey it is distinguished as Higher Floodplain Gravel. Numerous borings show that the fluviatile deposits attain 30 to 40 ft. O.D.

An aggradation surface of a similar height is suggested by numerous borings between West Ham, Wanstead and Ilford, the gravel surface ranging from 34 to 40 ft. O.D. in nine borings.

Between the Beam and Ingrebourne valleys (Dagenham and Rainham areas) the surface of the gravel lies between 28 and 38 ft. O.D.

At Shoeburyness, at the mouth of the present Thames estuary, a vast gravel sheet has a surface between 25 and 35 ft. O.D.

On the south side, opposite Shoeburyness, the river Medway affords further evidence. The gravel cap of the Isle of Grain at the mouth of the Medway appears to represent a level of about 30 ft. O.D. Several miles up the Medway, at Frindsbury, near Rochester, a terrace with sands and stratified gravel up to 25 ft. O.D. was described by Cook and Killick (1924). It contains at Aylesford, a few miles further upstream, a fauna with *Elephas antiquus* (Cook, 1923).

This evidence is strongly suggestive of a sea-level with a highwater mark of somewhat over 30 ft. O.D., which can only be the well-known Late Monastirian 7·5 m. sea-level. The fauna of this aggradation both at Brentford and in the Medway valley indicates a mild, temperate climate.

The Lower Floodpain Terrace and its pertaining sea-level will be discussed later on (p. 133). For the moment it is important that following the Tyrrhenian 100 ft. sea-level, two sea-levels at about 60 and 25 ft. can be recognized in the Thames as elsewhere, *i.e.* the Main and Late Monastirian levels. Of these, at least the lower corresponds to a temperate climate.

CLIMATIC EVENTS FOLLOWING THE TYRRHENIAN BUT ANTEDATING ONE OR BOTH MONASTIRIAN LEVELS.—The 60 and 25 ft. sea-levels supply two useful datum-lines in the history of the Thames valley following the 100 ft. sea-level. There is good evidence for at least one cold phase which occurred between the 100 and 25 ft. sea-levels, and possibly for several. It has been provided chiefly by J. P. T. Burchell (1933, 1934*a*, 1935*a*, 1935*b*, 1936*a*, 1936*b*), from the Ebbsfleet valley immediately east of Swanscombe.

THE TAPLOW BENCH.—In this area a phase of downcutting followed the aggradation to the 100 ft. sea-level. It cut through the deposits and into the solid Chalk at Swanscombe, eventually forming the bench on which the Taplow deposits rest at Crayford, Swanscombe, etc. This bench is at about zero O.D. and falls below O.D. further down the river (Bromehead, in 'Dartford Memoir,' 1924, p. 98). It represents a phase of low sea-level, presumably with a cold climate.

It has been suggested that this downcutting took place in two stages, the higher bench lying at about 30 ft. O.D. at Swanscombe (Dewey, 1932, p. 52; Burchell, 1933, p. 68; King and Oakley's 'Pre-Coombe Rock Erosion Stages,' 1936, p. 60). Though an interruption of the process of downcutting is possible, the evidence put forward is inconclusive, since benches at the intermediate heights are supposed to have been cut during oscillations of the Great Interglacial (see p. 124), and it will be very difficult to recognize as such a later bench formed at the same level as some earlier bench.

THE MAIN COOMBE ROCK.—However this may be, the downcutting can be associated with a phase of cold climate with intense solifluction which brought masses of disintegrated Chalk and Tertiary (*Coombe Rock*) down to about 10 ft. O.D. or even lower (Ebbsfleet valley from Baker's Hole down "to the marshes by Northfleet," Dewey, 1932, p. 49). Gravels filling channels in the Coombe Rock of the Ebbsfleet valley contained a cold fauna with many remains of the mammoth.

Following the deposition of the Main Coombe Rock, a considerable thickness of true loess was deposited (Fig. 41; subaerial loams, 4, 5 and 7 of Burchell, 1935*a*), with an intercalation of a solifluction horizon. Whether the cold climate evidenced in this manner is merely the continuation of the Main Coombe Rock phase, or an independent phase, is not quite certain, though the evidence of erosion between the two deposits suggests that they represent different phases (Burchell, 1935*a*, p. 90). If this subdivision which has been accepted by many workers (King and Oakley, 1936; Zeuner, 1936) can be verified, it will be of the greatest chronological significance.

Fluviatile deposits cap the Main Coombe Rock deposits at Baker's Hole, Ebbsfleet Valley (Dewey, 1932), as well as the loess in Burchell's section (Burchell, 1935*b*, p. 330). These afford a tentative correlation with the 60 and 25 ft. sea-levels.

BURCHELL'S SECTION OF THE EBBSFLEET VALLEY.—The section due to excavations by Burchell (Fig. 40; Burchell, 1933, 1935*a*, *b*; 1936*a*, *b*; Boswell, 1940, p. 257, fig. 1) is the more complete. It rests partly on Chalk

(at about 20 ft. O.D.), partly on the Main Coombe Rock, and the containing cliff " is cut through meltwater-gravel, Coombe Rock . . . and Chalk " (Burchell, 1935*a*, p. 90). This, in the opinion of Burchell, indicates a phase of erosion and separates the loams of the section from the Main Coombe Rock. We would, therefore, here be confronted with two cold phases following the 100-ft. sea-level and antedating either the 60 or 25 ft. sea-level, or both. Whilst the first of these cold phases would have been chiefly one of intense solifluction, the second would have been drier on the whole, loess being deposited. The loess series comprises, on the evidence of mechanical analysis, Burchell's Lowermost, Lower and Middle Loams (Fig. 41).

Mechanical analysis, pH-value, texture and reddish colour show that the top of the Upper Middle Loam bears a weathering surface which, judging

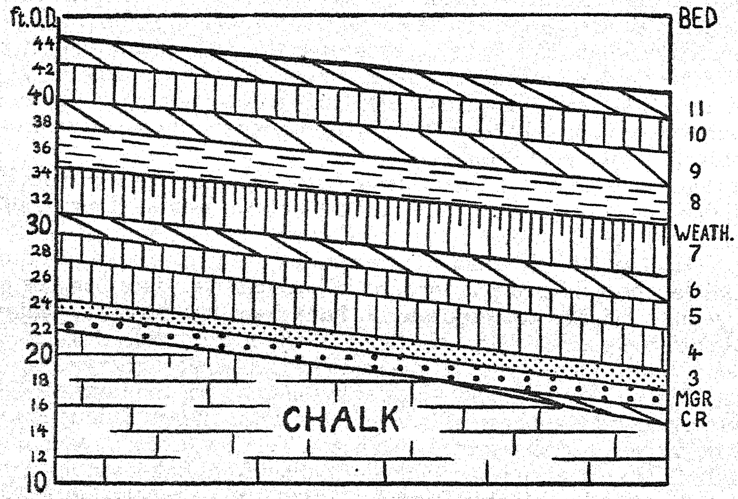


FIG. 40.—Section of the deposits of the Ebbsfleet Valley, near Swanscombe, Kent, at the site of Mr. J. P. T. Burchell's excavation. Based on publications and a manuscript profile by Mr. Burchell, with permission.

Beds.—(CR) Main Coombe Rock on Chalk, separated by erosional unconformity from (MGR) coarse gravel. (3) Fluviatile gravel ; in another section Lowermost Loam (loess) intercalated between (MGR) and (3). (4) Lower Loam (loess). (5) Lower Middle Loam (loess). (6) Solifluction. (7) Upper Middle Loam (loess), weathered on top. (8) Temperate Shell Bed. (9) Solifluction. (10) Uppermost Loam (loessic). (11) Solifluction. Compare Fig. 41.

by the unusually reddish hue, may have been formed in a climate somewhat warmer than the present. It is strongly reminiscent of the " argile rouge " of northern France. This buried land-surface represents an interglacial. It is covered by a grey silt bed, Burchell's Upper Loam, which contains a temperate shell fauna, determined by Mr. A. S. Kennard (Burchell, 1935*b*, p. 330). The drowning of a land-surface of considerable duration by this water-lain deposit is most readily interpreted by a rise of the sea-level to approximately the height of this land-surface, which is, according to figures kindly supplied by Mr. J. P. T. Burchell, 39 ft. O.D. at the locality of his

excavation. It thus appears to be connected with the Late Monastirian sea-level.

The temperate shell-bed is covered by solifluction deposits of a subsequent cold phase.

BAKER'S HOLE.—The section at Baker's Hole (Smith, 1911; Dewey, 1932) shows a coombe rock, considered as the main Coombe Rock, resting on Chalk at 40 ft. O.D. (Dewey, 1932), *i.e.* about 20 ft. higher than in Burchell's section. This is the Main Coombe Rock through which Burchell

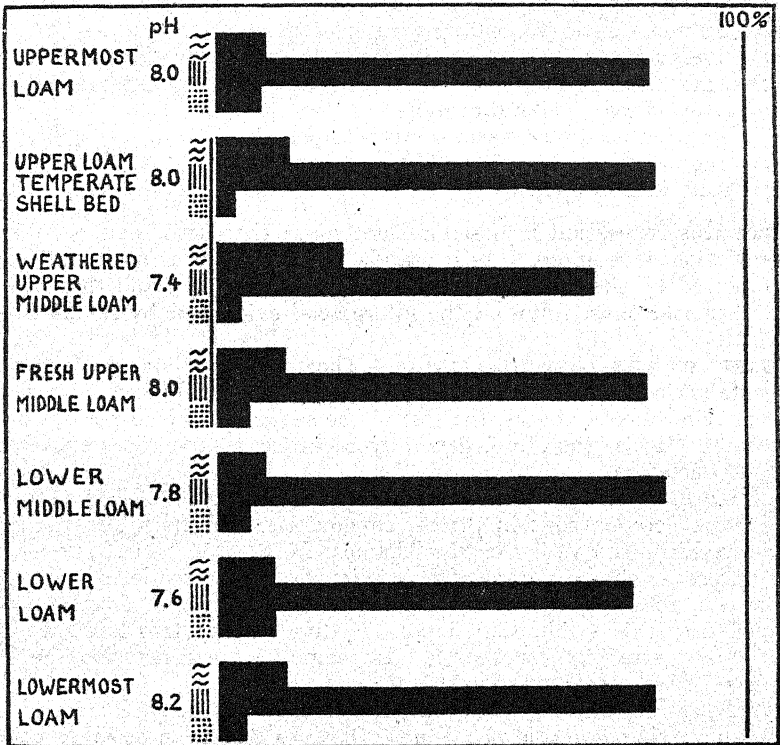


FIG. 41.—Mechanical analyses of the "loams" of Burchell's excavations, Ebbsfleet Valley. See Fig. 40. Showing loessic nature, and the weathering of the Upper Middle Loam. For signs used, see Fig. 26.

found his part of the valley cut. The Coombe Rock and some channels filled with a cold gravel are covered by a fluviatile series of gravels, sands and brickearth which suggests a gradually ceasing aggradation. Disregarding possible slight denudation, the aggradation would have reached up to 52 ft. O.D., or thereabouts. This figure reminds one of the 60 ft. sea-level of the Thames estuary.

BOTH MONASTIRIAN SEA-LEVELS REPRESENTED IN THE EBBSFLEET VALLEY.—If this aggradation actually represents the Main Monastirian level or, expressed in local terms, the top of the fluviatile Taplow Terrace, the second cold (loess) phase is not represented at Baker's Hole.

On the other hand, Burchell's section appears to contain the Late Monastirian, or Upper Floodplain, level, so that any deposits of the 60 ft. aggradation in this place would have been removed by denudation before the weathered land-surface was formed. The most likely sequence of events thus appears to have been :

	Climate.
(*a*) 100 ft. sea-level	Interglacial.
(*b*) Erosion, possibly to below zero O.D. . .	Glacial.
(*c*) Solifluction, Main Coombe Rock . . .	
(*d*) Unknown interval, ending with erosion .	—
(*e*) Loess and solifluction of Burchell's section .	Glacial.
(*f*) Aggradation of rivers to + 60 ft. O.D. . .	Interglacial.
(*g*) Drop of sea-level and erosion	—
(*h*) Weathering under warm-temperate climate .	Interglacial.
(*i*) Aggradation to + 35 ft. O.D.	
(*j*) Solifluction deposits	Glacial.

Since this succession is based on not more than two sections, further substantiation is required. As it stands, it suggests that two cold phases were followed by the two high sea-levels of 60 and 25 ft., and that at least one further cold phase followed the interglacial evidenced by the 25 ft. sea-level.

Phases of the Last Glaciation.—There is abundant proof that the temperate period of the 60 and 25 ft. sea-levels was followed by a period of one or several cold phases, the last in the sequence of cold periods of the Pleistocene. It is, therefore, generally regarded as the representative of the Last Glaciation.

In the area of Ebbsfleet and Swanscombe, Burchell (1936*a*) showed that a trail, with coombe rock in places, covered the Ebbsfleet Channel series and plunged into the valley of the Thames, from + 50 ft. O.D. to − 5 ft. O.D. It proves that a period of frost climate, with a sea-level lower than the present, followed the 25 ft. sea-level. In the same paper, Burchell described how this solifluction deposit is divided into two horizons by a bed of sandy, stratified brickearth. He came to the conclusion that two cold phases have contributed to this trail.

The Sunk Channels.—The suggestion that the Last Glaciation left traces of more than one cold phase in the Thames Basin can be substantiated by further evidence. The most important is supplied by the sunk channels, which are later than the Upper Floodplain Terrace.

There are at least two sunk channels, and possibly three. The latest of these is readily recognized by its filling, which consists of Postglacial alluvium (Pre-Alluvium Erosion Stage and Tilbury Filling Stage of King and Oakley, 1936, p. 69).

There is an earlier sunk channel at the bottom of which, in the Lea Valley, the subarctic peats of Ponders End, Angel Road and Temple Mills are found (Warren, 1912, 1914, 1916).

That the cold peats of Ponders End are at the base of the filling of a channel is borne out by Warren's sections (1912, p. 214; 1916, p. 170). The bench of this deposit lies at − 5 ft. O.D. at Temple Mills, about three miles from the mouth of the Lea into the Thames. It therefore belongs to a sunk-channel phase of the Thames.

The unfossiliferous aggradation of gravels which covers the Ponders End peat-raft beds has disappeared below the floodplain at Temple Mills(Warren, 1916, p. 170 ; surface 15 ft. O.D. ; alluvium 5 ft. ; gravel 15 ft.).

One might be inclined to identify this Ponders End-Temple Mills stage with the cutting of the sunk channel of the Tilbury stage. But at Hackney Wick, only half a mile downstream from Temple Mills (Warren, 1916, p. 172), a channel was found filled with gravel and with peat " resembling an ordinary Holocene peat." These deposits have a surface-level of + 15 ft. O.D. and reach down to − 5 ft. O.D. They are regarded by Warren as more Recent than the Ponders End stage. This indicates that a separate, later, channel exists here, so that two sunk channels are suggested up to this point.

Hedge Lane.—There is evidence, however, of a third, and earliest, sunk channel provided by Warren's cross-section of the Lea Valley at Hedge Lane, Edmonton (1916, pp. 170, 171). This author found that, apart from the eastern channel of the Lea (which contains the Ponders End, Angel Road and Temple Mills sections and also the present Lea) there is a western one containing peat beds *in situ* at Hedge Lane. These deposits rest on a bench at 20 ft. O.D. or lower (Warren, 1916, p. 168, footnote 2), and reach up to at least 52 ft. O.D., whilst in the corresponding part of the *eastern* channel, at Angel Road, the bench is at about 20 ft. O.D. and the gravel surface at about 34 ft. O.D.

The two localities are nearly two miles apart and separated by a ridge rising to 49 ft. O.D. (Warren, 1916, p. 167). This alone suggests that the two channels are independent formations and not two contemporary branches of the Lea. The latter alternative is rendered highly improbable by the difference in height of the aggradation surfaces. When the aggradation of Hedge Lane had reached 52 ft. O.D., the river could have played freely across the separating ridge into the eastern channel—if this was in existence already. Thus one finds that, if the two channels were contemporary, the aggradation would reach the same height of 52 ft. or over in both ; but since the Hedge Lane channel has in fact the higher aggradation, it must be the older.

The flora of the Hedge Lane peats has generally been regarded as identical with that of the Ponders End stage. But King and Oakley (1936, p. 62) found that " there is no definite evidence that the flora of the Hedge Land deposits is the same." Mr. A. J. Wilmott, whom I consulted about this flora, considers that there is no evidence in Reid's list (1916, p. 156) that the climate was different from that of the present time. The only possibly cool species is *Salix lapponum* L. That the Hedge Lane flora is different from the subarctic Ponders End type is apparent.

Thus there appear to be three sunk-channel phases in all, the Hedge Lane stage representing the oldest (with its filling), the Ponders End stage the second, and the Tilbury (Hackney Wick) stage the third, which definitely connects with the Present by the nature of its filling. Three low sea-levels are indicated in this manner, and three phases of the Last Glaciation.

Relation of the Sunk Channels to the Phases of High Sea-level.—The three aggradation surfaces of the channel-fillings are (*c*) the present surface of the alluvium, (*b*) the surface of the gravels of the Ponders End stage, and (*a*) the surface of the Hedge Lane aggradation. Since (*b*) never

	PERIGLACIAL AREA	MORAINIC AREAS	
	THAMES	EAST ANGLIA	WALES & IRELAND
PGl	TILBURY STAGE		
LGl 3	THIRD BURIED CHANNEL BENCH		"SCOTTISH RE-ADVANCE"
	PONDERS END AGGRADATION		
LGl 2	SECOND (PONDERS END) BURIED CHANNEL	HUNSTANTON BOULDER CLAY	NEWER DRIFT
	LOWER FLOODPLAIN TERRACE		
LGl 1	FIRST (HEDGE LANE) BURIED CHANNEL	? LITTLE EASTERN GLACIATION	GOWER OLDER DRIFT
LIgl	UPPER FLOODPLAIN TERRACE		25-FT. SEALEVEL
	EROSION		
	TAPLOW TERRACE		
PGl	EBBSFLEET LOESS	GREAT CHALKY BOULDER CLAY	
	MAIN COOMBE ROCK		
PIgl	BOYN HILL TERRACE		
$\mathrm{A_pGl}$	BOYN HILL BENCH	- THAMES VALLEY GL. NORTH SEA DRIFT	
	KINGSTON LEAF		
	200 FT. LEVEL	CROMER FOREST BED	
EGl	GRAVEL TRAINS	WEYBOURNE CRAG	
		NEWER RED CRAG	
	400 FT. LEVEL		

FIG. 42.—Attempted correlation of the morainic and periglacial areas of Britain. Compare Figs. 17, 24 and 33.

rises appreciably above (*c*) and disappears below (*c*) at Temple Mills, the sea-level of the aggradation of (*b*) appears to have remained below the present O.D. Therefore, the prevailing view which correlates these deposits with the Upper Floodplain Terrace (*i.e.* the 25 ft. sea-level) has to be abandoned. The Hedge Lane aggradation (*a*), however, forms a terrace. It has been referred to the Upper Floodplain Terrace by Warren (1916, p. 169), and to the Taplow Terrace by King and Oakley (1936, p. 62).

Considering the gradient of the surface from Edmonton to the mouth of the Lea, the Hedge Lane aggradation can be connected either with the Upper or the Lower Floodplain Terrace, but it is difficult to link it with the Taplow level of the Thames (60 to 70 ft. O.D.). But although this is true as regards the surface, we saw on p. 131 that the bench of the Hedge Lane deposits is no higher than the bench at Angel Road, and that both constitute sunk channels below the floodplain of the present Lea. It seems difficult therefore to regard the filling of either of these channels as earlier in date than the filling of the sunk channels of the Thames. This, to my mind, disposes of the correlation of the Hedge Lane aggradation with the Upper Floodplain Terrace, the only possible remaining correlation being with the Lower Floodplain Terrace.

Lower Floodplain Terrace.—It has been said previously (p. 126) that the Lower Floodplain Terrace diverges from the Upper below Bushy Park, and that its surface is slightly over 20 ft. O.D. at Barnes. This surface is met again further downstream in many places. Though it is difficult to state its height accurately, it is always a few feet below the Upper Floodplain Terrace and a few feet above the modern floodplain. Good evidence for this level has been brought forward by Cook and Killick (1924, pp. 150–154) from Halling in the Medway Valley, where a Palæolithic site with a skeleton of *Homo sapiens*, and with *E. primigenius*, *T. antiquitatis*, *Equus*, *Megaceros* and *Bos primigenius* was discovered. It rested on a fluviatile, apparently estuarine aggradation with a surface of 15 ft. O.D. The fossils plainly assign this aggradation to the Pleistocene, and the average sea-level would have been at a very few feet above the present O.D. King and Oakley (1936, p. 68) remark that numerous "eyots" of gravel which protrude through the modern alluvium may belong to the Lower Floodplain Terrace.

The climate of the Lower Floodplain Terrace aggradation was not temperate, but of a mixed, cold-temperate type, if one can trust the mammalian remains at Halling and elsewhere.

The age of the Lower Floodplain Terrace relative to the sunk channels is suggested by the conditions in the Lea Valley. Since the Hedge Lane aggradation appears to run into the Lower Floodplain Terrace, the latter was aggraded after the first sunk channel and before the second sunk channel. Thus it would represent the interstadial high sea-level intervening between the first and second phases of the Last Glaciation.

The high sea-level of the second interstadial, between the second and third phases of the Last Glaciation, would on the evidence of the Ponders End aggradation never have reached the present O.D. This explains why, in the Lower Thames, only two sunk channels, *i.e.* the first, and the second + third, can be recognized, and why the evidence for not more than one interstadial high level is available there.

Phase.	Sea-level.	Thames phase.	Typical localities.
Present	Zero O.D.	Present floodplain	
Postglacial	Rising to present level	Tilbury Stage, K. & O.*	Hackney Wick.
LGl_3	Cutting to low sea-level	Third buried channel=pre-Alluvium Erosion Stage, K. & O.	
$LGl_2/_3$	High, but remaining below zero O.D.	Filling of second buried channel	Aggradation covering cold deposits of Ponders End, Angel Road, Temple Mills.
LGl_2	Cutting to low sea-level	Second buried channel	Cold peats of Ponders End, Angel Road, Temple Mills.
$Lgl_1/_2$	High, a few feet above O.D.	Lower Floodplain Terrace aggradation= Halling Stage, K. & O.	Thames "eyots," Hedge Lane.
$LgGl_1$	Cutting to low sea-level	First buried channel=Buried Channel Erosion Stage, K. & O.	Bench of Hedge Lane deposit.
Late LIgl	25 ft. sea-level	Upper Floodplain Terrace aggradation	Brentford, City of London Flat.

* King & Oakley (1936).

LATE PLEISTOCENE OF THE THAMES: SUMMARY.—The table on p. 134 summarizes the sequence of events which can be discerned in the area of the Lower Thames from Upper Floodplain Terrace times onwards.

PIN HOLE CAVE, DERBYSHIRE.—The evidence afforded by the Thames for the tripartition of the Last Glaciation does not stand alone in the British Isles. A. L. Armstrong (1931) found three cold phases, considered by him as belonging to the Last Glaciation, in the section of the Pin Hole Cave, at Creswell, Derbyshire. Geologically, the first two cold phases are indicated by layers of rock debris (interpreted as the result of frost weathering), and the third by cave-earth immediately beneath a horizon of stalagmite. Palæontologically, the three cold phases are characterized by reindeer faunas. Details of the faunal succession are given in Chapter X, p. 268.

CLIMATIC PHASES OF THE BRITISH PLEISTOCENE: SUMMARY.—Thus the Thames Basin provides us with a very complex succession of climatic phases (Fig. 42). The Last Glaciation appears to fall into three distinct phases. The Last Interglacial shows two high sea-levels, the earlier of which was the higher. The Penultimate Glaciation is apparently divided into two phases, but the evidence for this so far comes from the Ebbsfleet area only. The Penultimate Interglacial may have to be divided into several phases, but unlike the Last Interglacial, the highest sea-level occurred late. The Antepenultimate Glaciation comprises two phases, the second of which reached the Thames valley (Hornchurch, etc.). Previous to this glaciation, the 200 ft. level indicates the Antepenultimate Interglacial. There is evidence for one or several cold phases preceding this interglacial.

The correlation of this part of the periglacial area of south England with the morainic succession of East Anglia, Wales and Ireland can best be effected by equating the three morainic phases of the Last Glaciation with the three sunk-channel phases found in the Thames, and by equating the 200 ft. level of the Antepenultimate Interglacial of the Thames Basin with the Cromer Forest Bed. That the last two belong to the same interglacial (though not to the same phase within this interglacial*), cannot be proved in Britain, but it is shown in the Somme, where the Forest Bed fauna occurs in the aggradation of the Milazzian sea-level (p. 90).

This correlation suggests that it was the earlier of the two great East Anglian glaciations (North Sea Drift Glaciation) that reached the Thames valley.

The general succession of the British Pleistocene is essentially similar to those of the morainic and periglacial areas of the Continent, although *a priori* a close agreement was not to be expected in view of the more oceanic climate of Britain.

The fact that the successions established throughout temperate Europe, from Russia to Britain, conform to the scheme of three phases of the Last Glaciation and two each of the earlier ones, can only have one meaning: that a major cause acting over the entire area determined the fluctuations of the climate during the Pleistocene.

* The low elevation of the Cromer Forest Bed is no obstacle to this correlation. Though deposited during an interglacial during which the sea-level was at one time as high as 200 ft. O.D., the Forest Bed may well date from a phase when the sea was not at its highest. Alternatively, tectonic changes of altitude have been suggested (Wooldridge's Braintree Line, 1928, p. 24).

CHAPTER V

THE ASTRONOMICAL THEORY AS THE BASIS OF AN ABSOLUTE CHRONOLOGY OF THE PLEISTOCENE

A. THE INEQUALITIES OF THE EARTH'S ORBIT.

AMONG the various factors which might have produced the curious fluctuations of the Pleistocene climate, those which cause the amount of solar radiation to change periodically have received much attention in recent years.

The *ad hoc* assumption that the radiation output of the sun changed periodically so as to produce (directly or indirectly) the glacial and interglacial phases cannot be proved and, therefore, cannot be regarded as satisfactory. If other, known and observable, factors can be found which explain in a simple way the fluctuations revealed by geological evidence, they are to be preferred to *ad hoc* assumptions of any description. Such factors indeed exist in the changeable elements of the earth's orbit. They are called the *inequalities*, or *perturbations*, and have periodicities of many thousands of years.

The perturbations influence the distance and position of the earth relative to the sun, and consequently produce fluctuations in the amount of solar radiation received by any particular locality, or zone of latitude, of the earth. It must be understood, however, that the quantities of radiation received, as calculated by the astronomers, apply only to the upper limit of the atmosphere, and not to the sea-level or the solid surface of the earth.* So far as the climate depends on the radiation received at the upper limit of the atmosphere, it is called the *solar climate*, but the actual climate as observed by meteorological methods depends on other factors as well. The translation of the solar climate into ordinary terrestrial climate is a formidable task and to some extent as yet unsolved. But if it is found that the periodical fluctuations of the solar climate resemble to a high degree the fluctuations of the terrestrial climate revealed by geology, it is reasonable to assume a causal connection between the two.

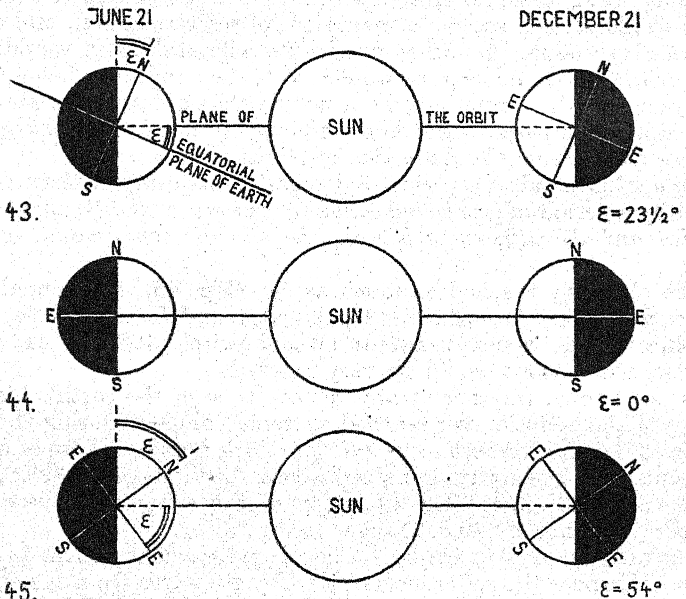
The importance of these considerations lies in the possibility of obtaining from the perturbations an absolute time-scale for the Pleistocene. It is necessary, therefore, to consider the perturbations of the orbit and their influence on the climate in some detail.

ORIGIN OF SEASONS AND CLIMATIC ZONES.—In order to understand the influence of the perturbations on the climate, it is advisable to recall the origin of the seasons and of the climatic zones by means of a few simple diagrams (Figs. 43–45). The earth revolves around the sun in an ellipse

* The present *average* value is 1·95 gramme calories per square centimetre per minute at the upper limit of the atmosphere. It is called the *solar constant*.

which is almost a circle, the sun being situated, not in the centre, but in one of the foci of the ellipse.

THE YEAR.—The period of revolution is the year, and its length has not varied for many millions of years. This was established by Korn's investigations of varved sediments of Lower Carboniferous and Devonian age (1938). In these the same rhythms and cycles are observed as in Pleistocene varved clays. The sunspot and other cycles of a duration of a few decades were of exactly the same length relative to the period of revolution of the earth in the Palæozoic as they are to-day. Since the sunspot cycle



FIGS. 43–45.—Diagrams illustrating the influence of the obliquity of the ecliptic. Cross-section of the orbit with the earth in midsummer and midwinter, respectively.

Fig. 43.—Obliquity (ε) = $23\frac{1}{2}°$ (present value).

Fig. 44.—Imaginary obliquity, $\varepsilon = 0°$. No seasons, but sharply marked geographical zones.

Fig. 45.—Imaginary obliquity, $\varepsilon = 54°$. Seasons very marked, but geographical zonation reduced to minimum.

in particular is caused by periodic changes in the atmosphere of the sun, whilst the length of the year depends on the earth's orbit, it is extremely unlikely that these two causally independent elements were both different from the present-day values in the Palæozoic and yet maintained exactly the same proportion. The same applies to cycles other than that of the sunspots. The conclusion is inevitable, therefore, that the year had exactly the same length 300 or 400 million years ago. For this reason, the period of revolution of the earth can be considered as unalterable for our purposes, as we shall consider only the one million years immediately preceding the present.

Obliquity of the Ecliptic.—Fig. 43 shows that the equatorial plane of the earth forms an angle of about $23\frac{1}{2}°$ with the plane of the orbit. This angle, which is the same as that between a line vertical to the plane of the orbit and the axis of the earth, is called the *obliquity of the ecliptic* (ε). It is the cause of the seasons, as well as one of the factors modifying the climatic zones.

Fig. 44 shows the imaginary position of the earth if no obliquity of the ecliptic existed ($\varepsilon = 0°$). The axis of the earth, around which it revolves once in 24 hours, would be vertical to the plane of the orbit, and it is easy to see that in this case, no matter which time of the year is considered, the equator would always receive a maximum of solar radiation, and the poles (theoretically)* none. In other words, the climatic zones would be very sharply marked, but no seasons would exist, the conditions being the same all the year round. From this we conclude that a *decrease of the obliquity* of the ecliptic (compared with the present value) *would diminish the seasonal differences but increase the distinction of climatic zones.*

On the other hand, if a period of decreasing obliquity of the ecliptic was followed by a period of *increasing obliquity*, the *seasonal differences* would be *intensified and the differences between the climatic zones* would once more *decrease.*

If the obliquity reached as much as 54° (Fig. 45), the annual total of radiation would be the same for the equator and for each pole, and the geographical zones would disappear (Milankowitch, 1930, p. 41). At the same time, the seasons would be very marked.

It is not known whether at any remote time of the earth's history the obliquity of the ecliptic ever reached extreme values. During those times which are of special interest to us and for which numerical values of ε have been calculated it has always remained within the limits of 21° 39′ and 24° 36′ (present value, 23° 27′). The obliquity of the ecliptic fluctuates with a period of approximately 40,000 years.

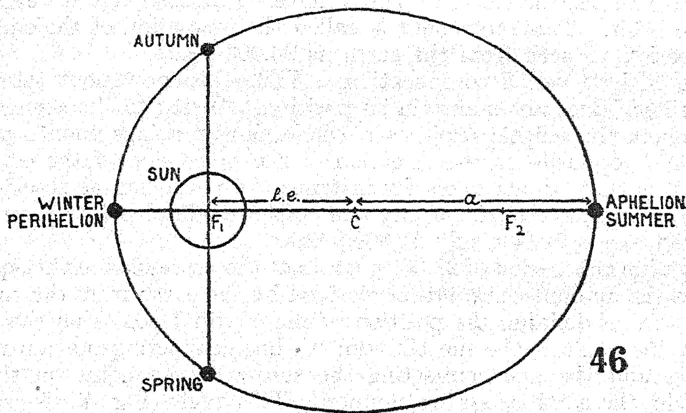
Eccentricity of the Orbit.—The second element which, by its fluctuations, influences the radiation received by the earth from the sun, is the *eccentricity of the orbit.*† As the sun occupies one focus of the ellipse of the orbit, it is easy to understand that its distance from the centre of the ellipse affects the length of the four seasons, as well as the distance of the earth from the sun at different times of the year (Fig. 46). Owing to the fact that the sun is not located in the centre of the orbit, there is a time of the year when the earth is nearer to the sun than during the remainder of the year. The point of the orbit which is nearest to the sun is called *perihelion*, whilst the farthest point is called *aphelion.* At present, the earth passes through the aphelion in north summer, and Fig. 46 clearly shows that, in this case, the summer portion of the orbit is longer than the winter portion. The summer half of the year in the northern hemisphere is at present 7 days 14 hours longer than the winter half-year.

The smaller the eccentricity, the smaller will be the differences in the lengths of the seasons, and *vice versa.* The eccentricity fluctuates with a period of 92,000 years.

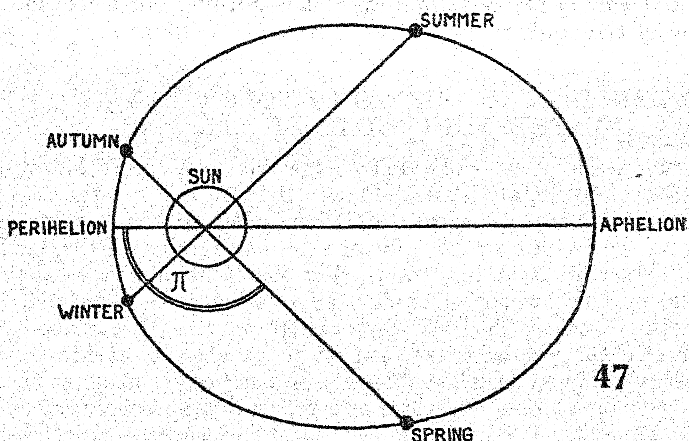
* Owing to refraction some light would reach the pole. The sun would appear always at about $\frac{1}{2}°$ above the horizon.

† Called "e," and equal to linear eccentricity ÷ half axis major.

Precession of the Equinoxes.—The third element in question is the *precession of the equinoxes* (π), *i.e.* the gradual migration of the four cardinal points (spring equinox, summer solstice, autumn equinox, winter solstice) along the orbit. The cause of the displacement is to be found in the oblation of the earth in connection with the obliquity of the ecliptic. The thickened equatorial belt of the earth is attracted by the sun* ; the part of the belt



46



47

Fig. 46.—Diagram illustrating the influence of the eccentricity of the orbit. Sun in one focus (F_1) of the elliptic orbit. Distance from centre (C) to aphelion or perihelion = half axis major (a). CF_1 = "linear eccentricity" (*l.e.*). Eccentricity as used in calculation, $e = \frac{l.e.}{a}$.

Fig. 47.—Diagram illustrating the influence of the precession of the equinoxes. The four cardinal points move along the orbit. This movement is measured by the angle π.

which is nearer to the sun is attracted more intensely than the distant part. This attraction results in a tendency to turn the earth's axis upright, but

* Apart from the sun, the moon and the planets contribute to the precession.

since the earth rotates continuously around its own axis, a conical movement of this axis is produced. It is the same movement that we all know of rotating spinning tops with an uneven load.

The inevitable consequence of this conical movement is that the position changes of the four cardinal points on the orbit (the connecting lines of which always form a rectangular cross). Conformably with the conical movement of the earth's axis, the cardinal points move by a small amount every year along the orbit. This movement is called the precession of the equinoxes, and its period, as seen from the earth, is 26,000 years.

There is, however, a complication. While this movement takes place the orbit itself does not maintain its position. Owing to the attraction by other planets the elliptic orbit as a whole slowly swings round, and this movement is opposite to the direction of the precession of the equinoxes. The result is that, if one takes for instance the perihelion as zero-point on the orbit, a complete circle of any one of the cardinal points requires *less* than 26,000 years, in fact only 21,000 years.*

It is within this period of 21,000 years that the precession of the equinoxes influences the amount of radiation received by the earth from the sun. The simplest way of defining the position of the cardinal points on the orbit is by giving the angle at the sun between the line connecting the sun with the perihelion, and the line connecting the sun with the point on the orbit occupied by the earth at spring equinox. This angle (Fig. 47) is called the *heliocentric length of the perihelion* (π); it is nothing but a measure for the precession of the equinoxes.

B. CONSTRUCTION OF CURVES OF SOLAR RADIATION BASED ON THE VARIATIONS OF ε, e, AND π.

HISTORICAL REVIEW.—The knowledge that the perturbations of the orbit influence the climate is very old indeed.† As early as the fifth century B.C. the philosopher Anaxagoras of Athens claimed that a change in the obliquity of the ecliptic would influence the habitability of the earth.

After Kepler, in 1609, had shown that the elliptical shapes of the orbits of planets and their speeds of revolution complied with certain simple laws of dynamics, Newton, in 1686, discovered the reasons for the planetary movements in the mutual attraction of the masses of celestial bodies and formulated the theory of gravitation. He also postulated that the planets must attract one another and that, as a result, small departures must occur from the simplicity of elliptic motion. He thus succeeded in interpreting the perturbations.

It was, however, not until more than 100 years after Newton that, thanks to the work of Lagrange and Laplace, it became possible to calculate the perturbations on a mathematical basis but, in view of their relatively small amplitudes, general opinion was at that time not in favour of a climatic interpretation of the phenomena. The task of calculation was again taken up by Leverrier at the end of the eighteenth century, and later by Stockwell, Pilgrim and Milankovitch.

* This is the answer to a question raised by Mr. R. G. Lewis in the 'Geol. Mag.,' 1935, p. 431.

† Fuller historical accounts are contained in Milankovitch (1930, 1936, 1938*b*).

The first to undertake the step from astronomy to climatology was Adhémar who, in 1842, tried to show that the erratic material which we now know to have been carried into the lowlands by the gigantic glaciers of the Ice-age was transported by periodical floods. These floods, he supposed, were caused by the accumulation of water and ice on one of the hemispheres during a period of cold winters caused by the precession of the equinoxes and the movement of the perihelion. His theory is, of course, out of date, but of great historical interest.

Later, when the drift hypothesis was replaced by the glacial theory, Adhémar's considerations were revived, though without success, since it became evident that the masses of ice accumulated in the glacial ice-sheet (as reconstructed on geological evidence) were not sufficient to produce the inundations postulated by Adhémar.

A considerable advance was achieved by Croll in 1864 (main publication, 1875), when he combined the effects of the changing length of the perihelion with those of the eccentricity of the orbit. Croll's theory says that, if in times of great eccentricity the line connecting the equinoxes approaches a position vertical to the line connecting perihelion and aphelion, the hemisphere whose winter happens to be during the passage through the aphelion will have a long and cold winter. Periods of cold winters were, by Croll, made responsible for the glaciations. His theory, however, though much appreciated for some time, did not prove to be satisfactory, since it postulated an alternation of glaciations on the two hemispheres and an increase of the glaciation in periods of cold winters, and since it treated the fluctuations in the obliquity of the ecliptic independently of the changes in eccentricity and precession. A modification of Croll's theory was put forward by Wallace (1880).

At that time the possibility of climatic fluctuations being due to changes of the obliquity occupied the minds of several other workers, but Croll (1875) showed that their conceptions were incorrect. One of them, Drayson (1871), suggested that the obliquity sometimes reached values much higher than it is considered possible by the astronomers. His theory has, unfortunately, gained a certain degree of publicity, and has even been referred to in text-books. It was refuted by Croll (1875, pp. 398, 410).

In 1890 Ball (1892) succeeded in improving Croll's theory by combining the influence of the obliquity of the ecliptic with the excentricity and the precession. He considered, however, the *total* effects on the two hemispheres only. In fact, these vary very little, and it is, as was shown above, the *distribution* of radiation over the various zones of latitude that is influenced considerably by changes in the obliquity of the ecliptic.

Similarly unsatisfactory have to be called the attempts made by Culverwell (1894), Hargreaves (1896) and Ekholm (1901). These authors, too, did not consider all three variable elements. Their results, interesting though they are from the historical standpoint, did not and could not agree with the evidence of past climates accumulated by the geologists.

More recently, Spitaler (1921) undertook once more to explain the glaciations by means of the perturbations, but he omitted to consider the variation of the obliquity of the ecliptic until 1934. Moreover, the figures which Spitaler uses disagree with those of other authors and are regarded as unsatisfactory by Milankovitch (1938*b*, p. 639), whose own figures for

the radiation received by the various degrees of latitude of the earth agree exactly with those of other mathematicians, such as Wiener, Lambert, Meech, Angot and Hargreaves (Milankovitch, 1938*b*, p. 599).

It is not surprising, therefore, that Hann (1908) considered the astronomical theories as useless. Indeed, the attempts mentioned to explain the climatic fluctuations of the Ice-age by means of one or two of the perturbations of the orbit or by an insufficient consideration of all three elements, could not produce results providing a basis for an absolute chronology of climatic fluctuations. Nevertheless, these authors were not far off the right track.

NUMERICAL CALCULATION OF THE PERTURBATIONS.—The final solution of the problem came from the mathematical side. Numerical calculation of the perturbations is an exceedingly difficult enterprise. The first results were obtained by Lagrange in 1782. The work was again taken up by Leverrier, whose calculations were published in 1843. They made their author famous throughout the world, since they resulted in the discovery of the planet Neptune. Leverrier had noticed that the masses and relative positions of the then known planets, Mercury, Venus, Earth, Mars, Jupiter, Saturn and Uranus, did not supply a complete explanation of all the perturbations observed, and he postulated, and predicted the position of, the more distant planet of the solar system, Neptune.* But the elements of the new planet could not be taken into account by Leverrier before they were accurately determined, and he therefore added the perturbing influence of Neptune in the form of adjustments to his original calculations.

This is probably the reason why, soon after Leverrier, Stockwell calculated the perturbations anew. His work took nearly 10 years; it was published in 1873.

Strangely enough, Leverrier's and Stockwell's results were not properly used by those early workers, like Croll and Ball, who attempted to explain the phenomena of the Ice-age by the fluctuations of the elements of the orbit, and it was not until Pilgrim, in 1904, used Stockwell's figures in order to combine the individual results, that the fluctuations of solar radiation were tabulated for a long interval with the view to interpreting oscillations of the climate. Pilgrim's figures cover approximately one million years, the year 1850 A.D. being taken as zero-point. Though Pilgrim's climatic theories were not more satisfactory than the earlier ones, his figures provided a very important basis for all subsequent work.

MILANKOVITCH'S CALCULATIONS.—More recently the work was again taken up by M. Milankovitch (1913, 1915, 1920), whose studies finally led to a complete success as regards the establishment of a chronology for the Pleistocene. After Milankovitch had elaborated new methods of calculation† he supplied, at the request of the well-known climatologist, W.

* Adams deserves equal credit for predicting Neptune (see Airy, *Monthly Not. R. astrom. Soc. London*, **7** (1846), p. 121). The actual discovery was made by Galle, and independently by Challis in England.

† It is incorrect to say, as Paterson (1941, p. 418) does, "that Milankovitch was but reproducing Croll's astronomical theory," as will be apparent to all who have gone into the matter. Similarly, it is a regrettable misconception to call the radiation curve as based on Milankovitch's work "Croll's curve as recalculated by Milankovitch," since Croll never produced a curve of this kind. Thirdly, it is untrue to say that Croll's theory was "apparently forgotten by, or unknown to, writers on this matter of late

Köppen, a diagram showing the changes of solar radiation for the last 650,000 years as experienced by the 55th, 60th and 65th degrees of northern latitude during the summer half of the year. These curves were for the first time applied to the climatic fluctuations of the Pleistocene as established on geological evidence by Köppen (in Köppen and Wegener, 1924), and subsequently by Soergel and many others. In calculating these curves (Fig. 48) the elements given by Pilgrim were used, who, in turn, had obtained them with the aid of Stockwell's formulæ.

At a later date Michkovitch and Milankovitch calculated a new set of tables, this time based on Leverrier's formulæ. This procedure provided a most important check since, as mentioned above, Leverrier's and Stockwell's methods of calculation were different. The new tables and curves (Fig. 49) obtained in this way agree in all essential details with the older ones. The only significant differences are found in the intensities of certain maxima and minima.

The later curve (and the tables providing the individual values for every tenth degree of latitude of both hemispheres—Milankovitch, 1930, 1938*a*, *b*) is more accurate than the earlier for several reasons, of which only one need be mentioned here. The relation of the mass of the earth to that of the sun was taken by Leverrier as 1 : 354936, by Stockwell as 1 : 368689, and by Pilgrim as 1 : 335172. Bauschinger (1920) was able to show that the most accurate value obtainable is 1 : 329350. This value has been used by Michkovitch and Milankovitch throughout their new calculations, whilst Pilgrim applied his value, better though it was than the earlier ones, only in part, being content with Stockwell's value in the remainder of the calculations. For this reason, the new tables and diagrams of Milankovitch may be regarded as the nearest possible approach to the real values for the fluctuation of solar radiation due to the inequalities of the orbit. They will henceforth be referred to instead of the earlier diagrams and tables.

Before embarking upon a climatological interpretation of Milankovitch's tables and diagrams it is necessary to obtain a clear idea of what information they supply, in order to understand their scope of applicability as well as their limitations.

Quite apart from increased numerical accuracy, the tables and curves supplied by Milankovitch have the advantage of enabling one to study separately (*a*) the seasons and (*b*) the zones of geographical latitude. Both these distinctions are, in fact, essential for the correct interpretation of the climatic fluctuations of the Pleistocene.

Distinction of Seasons.—There is a widespread impression among geologists and others not acquainted with climatology that the *annual* mean temperature is sufficient to characterize a certain climate. This is most certainly not the case, the distribution of heat over the year being equally important, not to mention barometric pressure and precipitation.

---

years." Milankovitch (1930), for instance, discussed Croll's theory with its merits as well as shortcomings. I have gained the impression from this and other paragraphs of Paterson's paper that, with respect to the astronomical theory, he did not read the relevant original publications carefully before pronouncing judgment on the work of the authors concerned. Paterson's paper became known to me after the present chapter was written, and it was impossible to insert more than occasional references to it.

48

49

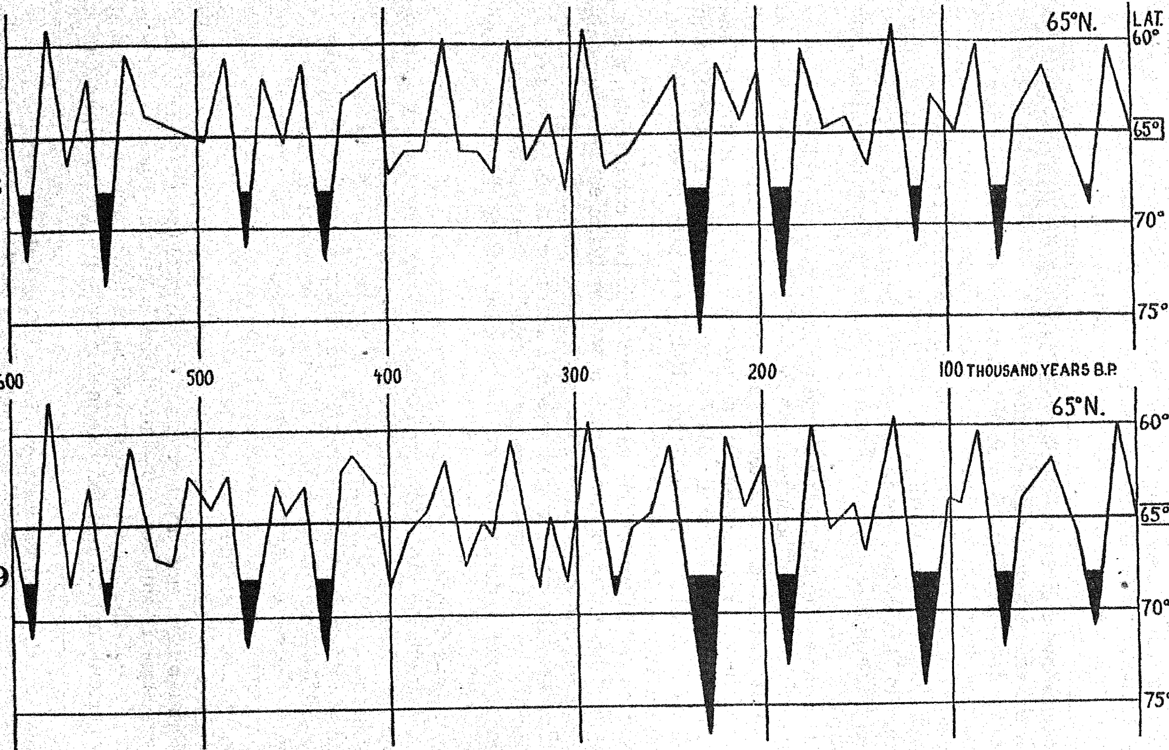


Fig. 48.—Summer radiation of lat. 65° N., for 600 thousand years before A.D. 1800 (called "before present, B.P."), expressed in imaginary displacement of geographical latitude. Based on Stockwell, calculated by Milankovitch, used and figured first by Köppen in 1924.

Fig. 49.—Same as Fig. 48. Based on Leverrier, calculated by Milankovitch (1930). "New diagram."

Fig. 51 shows the annual fluctuation of radiation for the last 185,000 years, expressed in degrees of centigrade as calculated by Milankovitch. It never exceeded $1\frac{1}{2}°$ C. Other authors regard the effect on temperature as even smaller; it is clear, therefore, that the annual mean fluctuated so little that its changes have to be regarded as climatically insignificant. The fluctuations as calculated for the summer and winter halves of the year were, however, much more considerable, and Fig. 52 shows that periods of high radiation in summer meant simultaneous winters with low radiation, whilst periods with low summer radiation were periods of high winter radiation. It is fortunate that the present-day conditions are very near the average between all extremes, and since present-day radiation supplies the zero-line in the graphs, they are easy to read.

Differences in the temperatures of the seasons, while the annual average temperature may be similar, distinguish the continental and oceanic types of climate; they are illustrated by a table, the figures for which were taken from Köppen's 'Elements of Climatology' (1931). In each of the four parts of this table, the localities are arranged beginning with the most oceanic and ending with the most continental climate.

	Mean.	(July)*	(January)†
(*a*) Annual mean between 8·3 and 8·7° C.			
Bealey, New Zealand	8·3	13·7	2·2
Edinburgh, Scotland	8·7	14·7	3·9
Berlin, Germany	8·6	18·0	−0·7
Niutschwang, Manchuria	8·5	24·4 (Aug.)	−8·9
(*b*) Annual mean between 9·6 and 9·8° C.			
Killarney, Ireland	9·7	14·8	5·5
London, England	9·8	17·3	3·4
Stuttgart, Germany	9·7	19·0	0·3
Budapest, Hungary	9·9	21·3	−2·1
Odessa, Russia	9·6	22·6	−3·7
(*c*) Annual mean between 11·1 and 11·7° C.			
Punta Galera, South America	11·2	14·0 (Jan.)	8·8 (Aug.)
Guernsey, Channel Islands	11·1	16·7 (Aug.)	6·2
Valladolid, Spain	11·2	21·2	2·0
Eriwan, Armenia	11·3	25·0 (Aug.)	−6·5
Peking, China	11·7	26·0	−4·7
(*d*) Annual mean between 20·2 and 20·8° C.			
Waimea, Hawaii	20·2	22·1 (Sept.)	18·2
Biskra, Algeria	20·7	31·9	10·6
Phoenix, U.S.A.	20·8	32·5	10·2

* Hottest month. † Coldest month.

If an increase of the amount of radiation received in summer means an increase in temperature on the surface of the earth and, correspondingly, a decrease in winter, colder winters, then the periods of high summer radiation would signify periods of increased continentality of climate, and the periods with decreased summer radiation periods of greater oceanity. Geological evidence has shown that changes in the character of the seasons played an important part in the glacial phases, and it is essential, therefore, to study the fluctuations of solar radiation separately for summer and winter. All tables and graphs, therefore, are constructed separately for the summer and winter halves of the years. Unfortunately it has become a widespread

10

practice among geologists to neglect the winter tables and curves completely, chiefly because the winter curves are very nearly the reverse of the summer curves, so that the summer curves alone provide an adequate picture.

CALORIC HALF-YEARS.—Difficulties would arise if, in the calculation of the tables, the summer half of the year were simply taken as astronomical spring + summer, and the winter half as astronomical autumn + winter. It was shown above that the lengths of the seasons depend on the variations of e and π, and that in certain phases the lengths of the summer and winter halves differ by many days. Thus, the astronomical summer half-year is, at present, on the northern hemisphere 7 days 14 hours longer than the winter half, but this value can grow to as much as 31 days 20 hours (Milankovitch, 1930, p. 46). If the calculations were based on such seasons of unequal length, the values for the radiation received would no longer be comparable. In order to obtain constant half-years, therefore, Milankovitch divided the year into two " caloric halves " of equal length in time, the summer half comprising all those days on which the daily amount of radiation received is larger than any daily amount received during the winter half.

CANONIC UNITS.—In the tables the variation of the radiation received by the earth from the sun is expressed in *canonic units*. These are obtained from the equations used in calculating the quantity of radiation received, by substituting 1 for the value of the solar constant and 100,000 for the sidereal year.* These canonic units are useful from the mathematical point of view. They can be used for comparing the relative intensities of radiation in time and space, but they do not, without some calculation, convey an idea of the absolute intensity of the changes of radiation. For this purpose, other methods of representation have been devised.

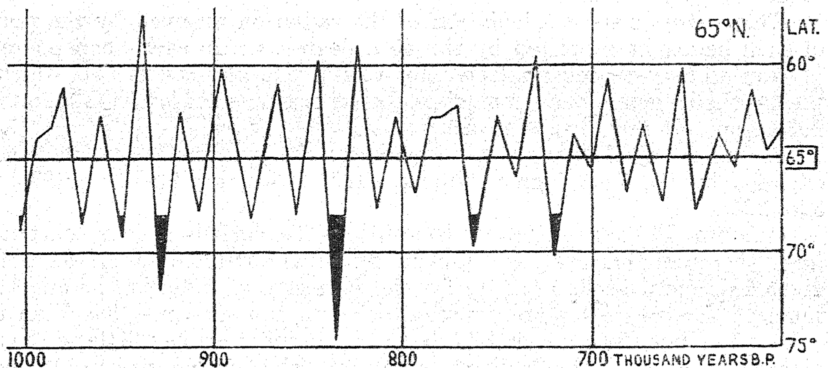
The tables on which the well-known graphs or " radiation-curves " are based, the result of very laborious work, were published by Milankovitch for every tenth degree of latitude between 5° and 75° of both hemispheres. The values were calculated for points on the time-scale at intervals of five thousand years before A.D. 1850 and for a great number of additional points where it proved desirable to make the graphs more accurate. The tables are contained in Milankovitch, 1930, pp. 128–134, and Milankovitch, 1938*a*, pp. 31–37. They cover a period of 600,000 years, but some graphs extend backwards still further (Fig. 50). Beyond 1,000,000 years, however, calculations have not been carried, since the intensities of the maxima and minima become less certain for the earlier ages.†

* To transform canonic units into gramme calories, note that 1·946 gramme calories per square centimetre and minute is the solar constant, and that the sidereal year has about 526,000 minutes.

† On the theory of classical mechanics it should be possible to calculate the values for any length of time back into the past. There is, however, a residual movement of the perihelion which cannot be explained by Newton's laws. It was Einstein who succeeded in interpreting this phenomenon, which has since become one of the most important proofs for his general theory of relativity (see, for instance, Russell, 1931, p. 131). This residual movement is found with all the planets, but is by far the largest with Mercury. It cannot as yet be incorporated in the calculations of the perturbations. Its influence is negligible for the last 600,000 years, and still small for the preceding 400,000 years, but previous to 1,000,000 years it assumes proportions which would render futile any calculation of the perturbations with the view to reconstruct the fluctuations of solar radiation (Milankovitch, 1938*b*, p. 649).

Distinction of Zones of Latitude.—The distinction of zones of geographical latitude is an essential complication which has been neglected by all workers except Pilgrim and Milankovitch. The influence of the fluctuations of the obliquity of the ecliptic on the radiation received by total hemispheres is comparatively small, but it is very great in certain zones of latitude

50



51

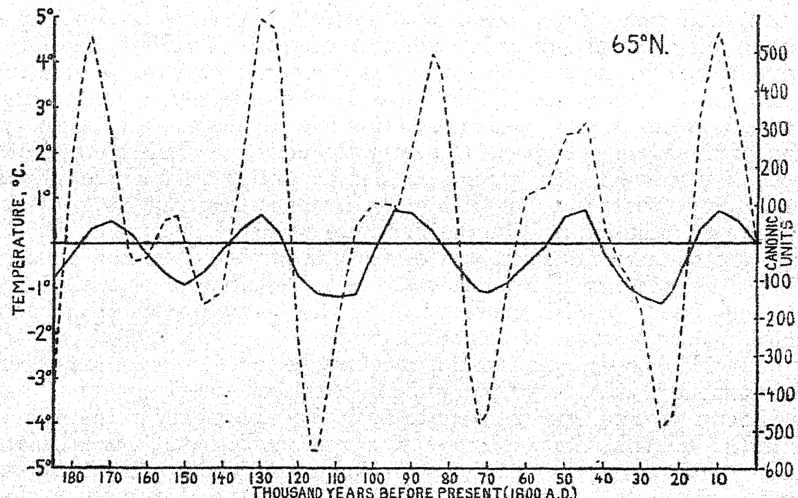


Fig. 50.—Extension of Fig. 48 to one million years B.P., calculated by Milankovitch in 1930, published by Eberl (1930).

Fig. 51.—Annual mean of radiation of 65° N. lat., full line. Summer radiation, broken line. Scale, left, degrees centigrade; right, canonic units. Based on tables in Milankovitch (1930).

and small in others. It will be seen that the steps of 10° Lat. chosen by Milankovitch are sufficiently close. Though the important point of the geographical latitude under which any area considered is situated has been emphasized from the start by Köppen and Milankovitch, it has frequently been neglected by geologists. It is necessary that, in considering the evolution of ice-sheets, the radiation changes in the zone of origin of the

ice-sheet be considered, as well as those in the zone into which the ice-sheet extends during the later phases of the glaciation. For regions outside the glaciated and periglacial areas, such as the Mediterranean and the tropics, the values for the respective zones of geographical latitude have to be used, with due consideration of secondary influences derived from higher or lower latitudes.

There also exists a calculation of the radiation received by the portion of each hemisphere limited by the 45th degree, *i.e.* in each hemisphere the portion which was most affected by Pleistocene glaciations and which, in the northern hemisphere, comprises the largest mass of land (Milankovitch, 1938*b*, pp. 664–667, figs. 324, 325.)

A similar calculation has been made for the portions of the hemispheres enclosed by the 55th degree (Milankovitch, 1938*a*, pp. 39–41 ; 1938*b*, figs. 326, 327).

GRAPHIC PRESENTATION OF RESULTS.—The various graphs constructed from the numerical values supplied by Milankovitch's tables have been given in several kinds of units for the intensity of radiation at any given time. The straightforward representation in canonic units has been used most often, but since it was felt that canonic units convey little to the non-mathematical mind, the first graphs ever published (in Köppen and Wegener, 1924) and many later ones gave, instead, the corresponding imaginary alteration of geographical latitude. A decrease of radiation received at a given place during a given season, as compared with the present amount, produces conditions as if this place were situated on a higher degree of latitude, whilst an increase of radiation is equivalent to an imaginary shifting of the place to a position nearer the equator. This method of representation conveys, at a glance, an idea of the intensity of the fluctuations. A locality situated on 65° N. lat., for instance, received, 10,000 years ago, a summer radiation as if its position were on 60° N. lat., whilst 23,000 years ago the summer radiation was of an intensity which is now met with on 71° N. lat. (Fig. 49). The drawback of this method of presentation is that it lends itself to misinterpretation, as the *imaginary* displacement of the locality may be taken as something real.

The ideal presentation would, of course, be that in degrees of temperature. The transformation of canonic units into degrees of temperature is, however, a difficult process, and the way to achieving it is paved with obstacles and pitfalls. Milankovitch, in his more recent publications, has calculated the theoretical movements of the snow-line corresponding to the fluctuations in canonic units. This is, for the purposes of the Pleistocene geologist, a readily comprehensible way of showing the fluctuations of radiation. Milankovitch has also undertaken to express the fluctuations of solar radiation in centigrades of temperature (1938*b*, p. 652 ; see Fig. 51). Other workers, however, regard the effect on temperature as smaller than Milankovitch does (Simpson, 1940). Since this is a problem of climatology, its bearing on the theory of glaciation will be discussed later on (pp. 150–154). Here it suffices to emphasize that Milankovitch's formulæ merely supply those differences in temperature which would be produced by a given change in intensity of radiation at sea-level in a perfectly quiet atmosphere. The ensuing modification of the meteorological conditions is not, and, for the time being, cannot, be expressed in this manner.

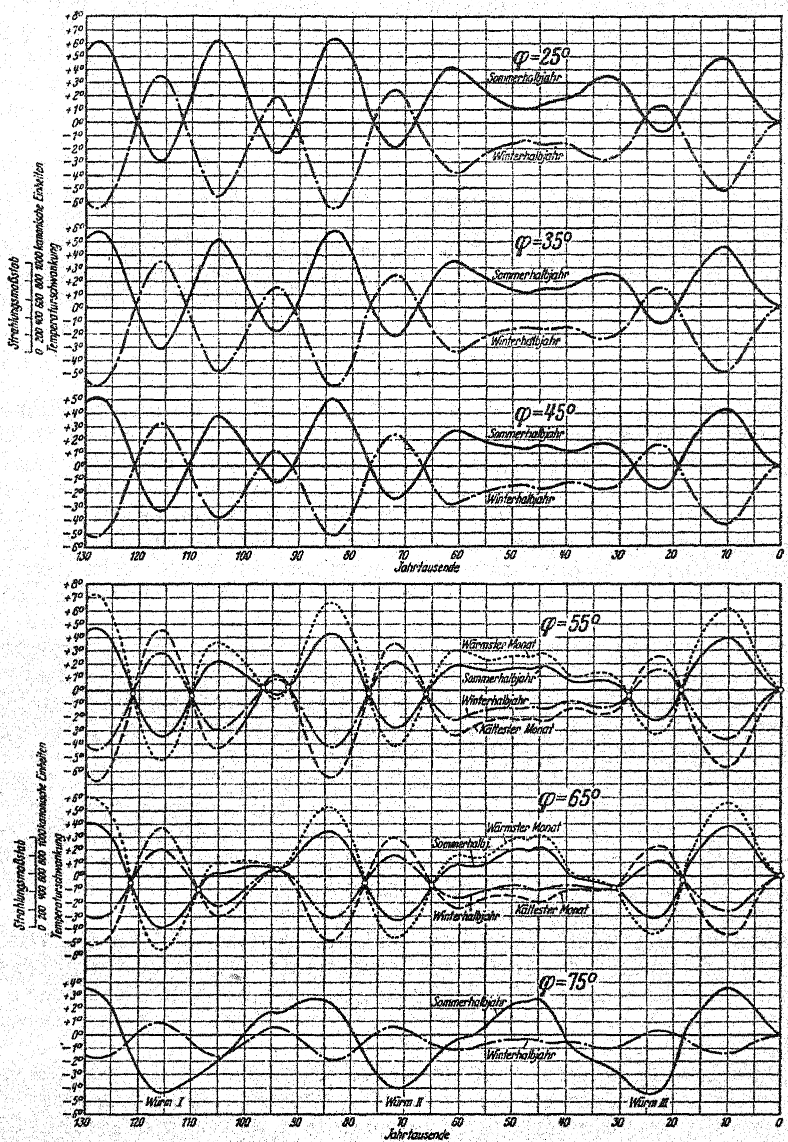


FIG. 52.—Summer and winter radiation for the last 130 thousand years, for latitudes 25° to 75° N. Summer half-year, full line; winter half-year, –·–·–. Warmest month, ... ; coldest month, – – – . Deviation from the present given in degrees centigrade, scale in canonic units added. From Milankovitch, 1930, pls. 3, 4.

Since the method of representing the intensity of radiation does not affect the shape of the curve, it does not matter which kind of graph is resorted to in interpreting geological evidence. The best is, perhaps, after all that in canonic units, since it does not imply any considerations beyond the actual amount of radiation received on the upper limit of the atmosphere.

c. RADIATION CURVES AND GLACIAL PHASES.

Introduction.—The fact that the amount of radiation, received by the earth from the sun, fluctuates as described in the preceding parts of this chapter has been known for some time, but the numerical elaboration has taken many decades, and the tabular and graphical methods of representing the combined effects of the astronomical elements have been achieved only within the last 25 years.

The probable effects of the fluctuations of radiation on the climate of the earth could not be studied in detail until the radiation tables and curves had attained their present form, so that most of this work dates from the last 10 or 20 years. Much of it has not yet found the appreciation it deserves, and it is often assumed that a haphazard superposition of a radiation curve on some succession of climatic events constitutes an act of scientific dating. This mistaken view accounts for much of the scepticism displayed by some scholars with regard to the absolute chronology of the Ice-age.

Snowline and Radiation.—An argument showing how closely climate is determined by radiation, in particular how the height of the snow-line depends on summer radiation, has been brought forward by Milankovitch (1938*b*, p. 641). It is illustrated by means of Figs. 53 and 54. Fig. 53 gives in canonic units the radiation at present received in summer (full line) and winter (broken line) by the various degrees of latitude. Fig. 54 shows the actual, observed or calculated, height of the present snow-line, according to Köppen. The curve of summer radiation proves to agree closely with that of the snow-line. In both the equatorial depression lies slightly north of the equator, and in both the southern peak of the curve is higher than the northern. If one analyses these curves mathematically one obtains a correlation factor as high as 0·83 for the entire curves, and for the portions between 40° and 90° N. lat. (in which subsidiary climatic disturbances such as the precipitation deficit of the dry belts are ruled out) the correlation factor is 0·996. A causal connection between the curves is, therefore, highly probable.

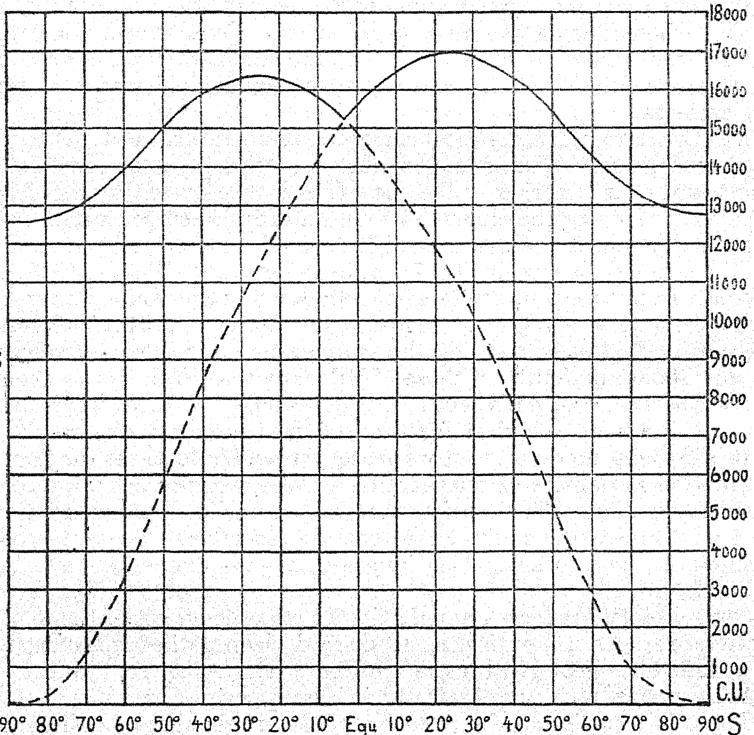
On this basis Milankovitch attempted to correlate changes in the radiation with movements of the snow-line (1938*b*, p. 649), and found that, theoretically, one canonic unit corresponds to a vertical displacement of the snow-line by 1·094 m. In nature, considerable deviations from this value must be expected locally, due to the local climatic conditions. Thus, it is chiefly of theoretical value, but it gives some idea of the magnitude of the changes that may be expected to result from oscillations of the radiation.

Magnitude of the Effects of the Fluctuations of Solar Radiation.—This brings us to the difficult question of the order of magnitude of the modifications suffered by the climate of a locality as the result of the

periodic fluctuations of summer and winter radiation. The views of workers diverge widely in this respect.

The paramount difficulty is that these effects can only be expressed in

53



54

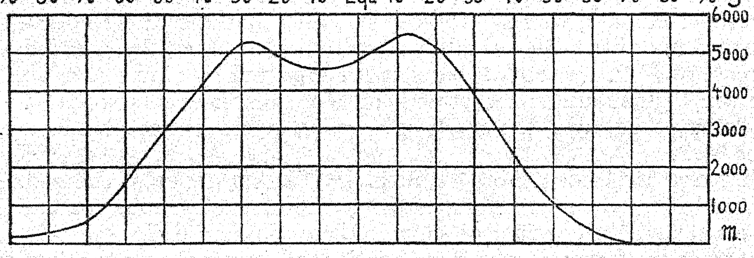


FIG. 53.—Present-day summer radiation (full line) and winter radiation (broken line) for every degree of latitude, expressed in canonic units. Calculated by Milankovitch (1938*b*).

FIG. 54.—Present-day snowline, in metres above sea-level, for every degree of latitude. After Köppen, in Milankovitch (1938*b*).

degrees of temperature irrespective of the influences of precipitation, etc. Several authors have tried to take this into account.

Milankovitch (1938*b*, p. 652) used the fact that, on the average, the temperature falls by 1° C. for each 150 m. of vertical ascent during the warmer part of the year. Thus, 150 m. of displacement of the snow-line, or roughly

150 canonic units, correspond to one degree of centigrade in change of temperature. This figure is largely hypothetical, and the actual values must have differed from it in many cases. Simpson (1940), for instance, pointed out that they cannot apply to the North Atlantic Ocean in latitude 55° N., where during the first phase of the Penultimate Glaciation the winters would have been warmer than the summers. This, however, does not disprove Milankovitch, who expressly confined his work to the large land surfaces.

Even on land, the theoretical change of temperature need not correspond to an actual one. Wundt (1938*a*) discussed this point in some detail, and emphasized that lowering of the snow-line can be caused by an increasedly oceanic character of the climate, without a drop in temperature. He found that a reduction of the seasonal difference of summer and winter by 1° C. would depress the snow-line by 78 m. in the average (Wundt, 1938*b*).

Apart from these objections to the direct and unrestrained interpretation of the theoretical changes of temperature, Simpson (1940) has designed a different method of calculating the temperature, and obtained values which are only about one-fourth of those of Milankovitch. I do not feel competent to say whether Simpson's method, which aims at actual values and takes into account meteorological factors, provides more reliable results.

It is evident, however, that we are as yet unable to assess the fluctuations of radiation in degrees of temperature. Some workers attribute to them a considerable direct effect; most workers are inclined to regard the direct effect on temperature as moderate but the secondary effects (see below) as considerable, and others, like Simpson, regard the effect as altogether negligible.

Our inability to assess numerically the climatic effects of the fluctuations of radiation does not entitle us to discard them as insignificant unless we have sufficient geological evidence for their being so. But geological evidence points most emphatically in the opposite direction.

Thus, in considering the probable effects of changes of radiation on the terrestrial climate, we have to keep in mind that the direct effects on temperature may have been small. A reduction of about 2° C. in July and an increase of 1° C. are the largest changes admitted by Simpson (1940), though Köppen, Milankovitch and others consider greater effects probable. In the following paragraphs, the small figures just given are accepted as a basis for discussion.

EFFECT OF REDUCTION OF SUMMER TEMPERATURE.—The reduction of summer temperature resulting from a decrease of summer radiation must have reduced the melting of snow and ice, depressed the snow-line and, in this manner, favoured the preservation of existing and the formation of new glaciers. This view is held by most meteorologists who have studied the problems of the snow-line (Köppen, 1924; Ahlmann, 1924). For mountain areas of the temperate zones, such as Scandinavia or the Alps, therefore, it can be said that periods of hot summers tend to raise the snow-line whilst periods of cool summers lower it. It was in the first instance for this reason that, in 1924, Köppen correlated the glacial phases with the summer minima of radiation.

The effects of the depression of the snow-line are intensified by the peculiar distribution of precipitation with altitude. This was pointed out by

Brooks (1926, pp. 183, 308), who relied upon ideas developed by Paschinger (1923), and whose words I am following in a shortened and slightly modified form:

"As we go upwards in a mountainous country, the total amount of precipitation increases to a certain level, above which it again decreases. With increasing height, also, the proportion of total precipitation which falls as snow becomes steadily greater. Hence we can distinguish a level of maximum rainfall, and above that a level of maximum snowfall (in the Alps at 1200 to 1650 m., and 2400 m., respectively). The latter is often very sharply marked; it depends upon the winter conditions. The snowline, on the other hand, depends mainly on the summer temperature. At present in the Alps the snowline is about 600 m. above the level of maximum snowfall. Suppose now the summer temperature decreases while the winter temperature remains unchanged. The snowline will descend, and if the decrease of summer temperature reaches 6° F. (3·3° C.) the snowline will coincide with the level of maximum snowfall. The supply of snow available for glaciers will be greatly increased and this stage will see a great development of glaciers."

Thus it appears that in periods of reduced summer radiation more ice survives (*a*) because of the smaller amount of heat radiation reaching the snow or ice surface, and (*b*) because of the depression of the snow-line towards the line of maximum snowfall.

Effect of the Increase of Winter Temperature.—Under certain conditions warmer winters also will encourage the growth of ice-sheets. If the winter temperature is much below freezing-point a slight rise is not likely to affect the glaciers. There is, however, no doubt but that in certain important parts of the European area of glaciation the supply of snow was greatly increased as the result of mild winters acting on existing snow- and ice-fields. The effect of a rise of temperature in the neighbourhood of an existing ice-field was demonstrated by Simpson (1938). He placed some water in glass cylinders and closed them with a small chamber containing solid carbon dioxide, to represent the ice-cap. If the water at the bottom of the jar is slightly heated, convection of the air and evaporation of the water are greatly increased and, with them, condensation over the "ice-cap," resulting in a heavy cover of ice crystals on the cold chamber. One can readily compare the air above the warmed water to the air above the Gulf Stream west of Scandinavia, and the cold chamber to the high mountains of Scandinavia. Any period of warming up, whether during the year as a whole (as assumed by Simpson), or during the winter only (as assumed in the present discussion), must bring increased snowfall to the Scandinavian mountains.

The increased snowfall in certain mountain areas during periods of warm winters has been stressed and its various aspects discussed by Beck (1938, p. 141) and Wundt (1935).

Increase of snowfall would also occur in areas where the winter temperature is not much below freezing-point and where a rise towards freezing-point would greatly increase the frequency of snowfall. 76 per cent. of the snowfalls occur at temperatures between + 4° and − 4° C. (Wundt, 1935, following Kassner). This maximum near freezing-point is a well-known phenomenon.

Effect of a Period of Greater Oceanicity on the Climate of Europe; Summary.—It is impossible here to go further into detail. From what has been said, however, it is apparent that a period of increased oceanicity, as suggested by the phases of decreased summer radiation and increased winter radiation, although the effects measured in degrees of temperature may be quite small, would, in temperate Europe, increase the glaciation of Scandinavia and of the Alps, and create a number of new small centres of glaciation, as for instance in the Scottish mountains (Bonacina, 1938; Sölch, 1932). If one accepts, in place of the very small temperature changes calculated by Simpson, those calculated by Milankovitch or some figure between the two, the effects would have been correspondingly greater.

Influence of Topography on European Glaciation.—No glaciation would develop if all Europe consisted of lowlands. It is the existence of the Scandinavian mountains, the Alps and, to a minor degree, the Scottish Highlands, that brought about the glaciation of vast lowland areas at low latitudes during the phases of decreased summer radiation.

Scandinavia was by far the greatest of the European centres of glaciation. It is worth while, therefore, to consider the changes which would result there from a period of decreased summer and increased winter radiation. Fortunately, H. W. Ahlmann has provided most valuable information concerning the snow-line and the amount of precipitation at various altitudes (Ahlmann, 1924).

In southern Norway, between 60° and 62½° N. (Kvitingen to Romsdalen), the height of the present snow-line varies between 2200 and 1300 m. above sea-level. In northern Norway, between 65½° and 72° N. (Velfjord to Alten-Kvaenangen) it varies between 1500 and 1000 m.

Ahlmann found that the precipitation as recorded by the valley stations is much smaller than actual amount falling on the mountains. He obtained the latter with the help of the run-off measured in the rivers. The amounts obtained in this way vary, for 21 stations given, between 115 and 380 cm. (45 and 149 inches) per year. They are among the highest for Europe. Now, if the snow-line is depressed during a period of cool summers, a large area of the Scandinavian mountains receiving heavy precipitation, but at present unglaciated, would be included in the glaciated level. Much of the unglaciated country between 66° N. (Svartisen Peninsula) and 70° N. (Tromsö) lies above 1000 m. If the summer temperature decreased by 2° C., the snow-line would be depressed to between 1200 and 700 m., and the existing small areas of glaciation would join up to form an almost continuous ice-sheet extending over the northern part of the Scandinavian mountains. Moreover, this ice-cap would receive a very large amount of snowfall as shown by the figures given.

If we now add the effect of the warmer winter coupled with a period of low summer radiation, with its increase of convection and of condensation over snowfields, it seems probable that such a period, though its effect on temperature might be slight, would result in a very considerable increase in the glaciation of Scandinavia. The peculiar topography of Scandinavia would cause much of the ice to flow eastwards into the basin of the Baltic Sea.

It may be objected that there is a great difference between such fluc-

tuations of the snow cover in restricted areas and a full-scale glaciation. Quite apart from the fact that a very small change has been assumed in the present discussion, a larger one as used by Köppen (1935), producing much more conspicuous results, it is the secondary effects of an ice-cap on the climate that change a locally restricted phenomenon into one of continental dimensions.

D. SECONDARY EFFECTS OF AN ICE-SHEET ON THE CLIMATE.

Once an ice-cap of comparatively small dimensions has been formed in the manner described a number of re-intensifying factors come into play. They are collectively called the "secondary effects."

ALBEDO.—The most direct of these is the loss of heat by reflection, called *albedo,* which leads to a considerable cooling of the ice-body and of the surrounding air. Its great importance for the intensification of glacial phases has been pointed out by many writers, notably by Brooks (1926), Milankovitch (1930), and Wundt (1933, 1935, 1938*b*). Milankovitch (1938*b*, p. 663) included this effect in his calculation and produced curves showing its influence, combined with that of the solar radiation, on the snow-line for the parts of the earth north of Lat. 55° N., and south of Lat. 55° S. (his figs. 326, 327).

The total albedo of the earth in its present state has been variously calculated as between 40 and 45 per cent. (43 per cent. being an acceptable value). So much of the radiation received from the sun is normally reflected, taking the average of all kinds of light and dark surfaces of the earth. A very large portion of the light surfaces is represented by clouds, the importance of which is explained by the fact that, at present, the clouded portions of the earth comprise as much as 54 per cent. of its total surface (Brooks, 1927). Changes in the cloudiness, therefore, will affect the albedo of the earth considerably. This has been pointed out by Simpson in many of his papers.

The albedo of a light surface, such as clouds, ice or snow, is as high as 80 per cent. (Brooks, 1926; Wundt, 1933), whilst that for the open ocean and for forests may be as low as 3–5 per cent. Light-coloured soils may have an albedo as high as 24 per cent. (values from Wundt, 1933). Similar values are given by Angström (1925), namely 80 per cent. for glaciated areas and 20 per cent. for unglaciated areas.

It is quite evident that the loss of heat due to albedo over an ice-sheet helps to preserve it. Brooks (1926, p. 128), using Angström's values, found that the heat lost by albedo from an ice-sheet in temperate latitudes would be sufficient to melt 30 ft. or 9 m. of ice per year. The cooling effect of the albedo grows as the ice-sheet grows, so that this mutual intensification must, if sufficient time is available, have great results, although the initial accumulation of snow or ice may have been small. All authors who have studied the growth of the Pleistocene ice-sheet have attached great weight to the albedo effect, since, in this way, the difference between a slight initial drop of the snow-line of some 200 to 400 m. and its depression during the major glacial phases of 1100 to 1300 m. can be accounted for.

It is difficult, however, to assess in degrees of temperature the effect of the albedo on any particular ice-sheet. Wundt, therefore, calculated the effect of a glaciation on the albedo of the entire hemisphere concerned. He

divided the surface of the earth into light, medium and dark areas, using Brooks's 10 degree fields as a basis. The effects of cloud were also taken into account. He found, by two independent methods, that the albedo of the northern hemisphere was increased by 3·9 per cent. (Wundt, 1933) or by 3·2 per cent. (Wundt, 1938*b*). In order to obtain a rough value for the effect upon temperature of this increase of albedo, a formula by Exner was used in 1933, and Stephan's Law combined with a formula by Milankovitch in 1938. The depression of temperature was, according to the two different modes of calculation, 4·8° C. or 4·1° C. for the northern hemisphere.

Taking the smaller figure and applying the commonly accepted value of 1° C. per 150 m. of depression of the snow-line, a general average depression of the snow-line of the northern hemisphere of 600 m. would have been caused by the increased albedo alone. This, added to the initial depression of 2–400 m., brings us near to the actual depression during the Last Glaciation which, in the Alps, amounted to about 1100 m.

These calculations cannot claim to yield precise results. They do, however, show what the order of magnitude of the effects of albedo on ice-sheets is, and that the original growth of ice-sheets during a phase of decreased summer radiation, plus the secondary effect of albedo, suffice without more to explain the observed depression of the snow-line during one of the major glacial phases of the Pleistocene.

The Glacial Anticyclone.—We have now to turn to those secondary effects that an ice-sheet exerts on the circulation of the air. The first and most important of these is closely linked with the albedo phenomenon; it is the accumulation of cold and heavy air over the ice-sheet. This heavy air constitutes an anticyclone which, if it attains a sufficient size, will interfere with the ordinary, non-glacial, circulation of the atmosphere.

It is well known that in the winter in temperate Europe, snow-cover and bright sky are associated with high barometric pressure and east winds. Anticyclonic conditions exemplifying the conditions of an ice-cap occur over Europe practically every year.

A permanent snow-field or ice-cap must have a certain minimum size for an active anticyclone to develop over it. It is easy to understand that a thin stratum of cold air over a small ice-cap will not bar the way to cyclones passing through the area. Brooks (1926, p. 69) has made an interesting attempt to determine the minimum size of an ice-sheet capable of sustaining a stable anticyclone.

According to Brooks, the greater part of Antarctica is immune from travelling depressions. The ice-cap of Greenland, though smaller, is still broad enough to prevent the influence of the majority of large depressions from extending to its centre. On the other hand, even smaller ice-masses like those of Iceland and Spitzbergen have little effect on pressure distribution. From this Brooks concludes that the critical point lies between the diameters of Greenland and Iceland, and that the diameter of a circular ice-sheet must attain 700 to 1000 miles before it can dominate the pressure distribution by pushing travelling depressions out of their way, compelling them to pass around the ice-covered area instead of traversing it.

In the concluding sentences of his discussion, Brooks alludes to the change of climate revealed by the flora after the Last Glaciation. The

retreat, or rather melting down of the ice, was a very rapid process, yet it was interrupted by a halt, the Salpausselkä Stage (p. 40). It is the view of Hyyppä (1933), as well as of Köppen (1934), that this stage, which lasted only for some 700 years, can be explained without assuming a drop in temperature. According to these authors the Scandinavian ice-cap had by that time become so small that its anticyclone deteriorated and depressions were able to enter the Baltic more frequently. This brought an increase of precipitation which, for a short time, may have increased the snowfall and thus caused a short halt in the retreat.

The interesting feature of this explanation, unnoticed by its authors, is that the diameter of the Scandinavian ice-cap during the Salpausselkä Stage had been reduced to about 1000 km. or 625 miles, a figure which agrees very closely with the minimum size deduced by Brooks.

Deviation of Barometric Depressions.—The establishment of an anticyclone over Scandinavia and the Baltic, probably extending east into Asia and certainly south into central Europe during the more intense glacial phases, modified the climate profoundly in many respects. Four of these may now be mentioned :

(1) The barometric depressions which bring rain to Europe and arrive, generally speaking, from the west or south-west and penetrate into the Continent, were deflected by the glacial anticyclone. Many were forced to take the southerly course and to enter the Mediterranean, bringing an increase of rainfall to this zone. This conception is an old one (see, for instance, Eckardt, 1909), and it has been used by numerous authors to explain the pluvial phases in the Mediterranean. The pluvials will be considered separately (Chapters VII and VIII), so that it suffices here to say that conditions in the Mediterranean were somewhat more complicated than is generally assumed.

Another group of depressions was probably deflected northwards, bringing extremely unsettled weather and heavy precipitation to the north Atlantic in the early part of a glacial phase. Western Scandinavia is likely to have benefited by this, and received further supplies of snow at a time when the ice-cap required enormous amounts for its sustenance and growth.*

As the cover of drift ice in the north Atlantic grew, however, this northern route of the depressions would have been barred to an increasing extent, with a consequent reduction of precipitation. This must have had important repercussions on the feeding of the Scandinavian ice-sheet (see point (4), below).

East Winds.—(2) The winds blowing from an anticyclone in the northern hemisphere arrive from the north-east quadrant along its southern edge. The areas adjoining the Scandinavian ice-cap in the south, therefore, were dominated by easterly and north-easterly winds, which, coming from an ice-sheet, were dry and cold. They must have been particularly strong

* The later stages in the growth of an ice-sheet must not be visualized as being entirely due to the supply of snow to the original centre of glaciation. Snow which falls near the periphery of the growing ice-cap, and ground-ice formed in the *tjæle* see Chapter I) would have accumulated and formed immense masses of dead ice before the moving glacier joined up and began to incorporate them. This process speeded up the growth of the ice-cap and possibly explains the rapid extension of the ice-cap from Scandinavia into north Germany, as the reverse process of dead-ice formation during retreat explains the rapidity of the latter.

in summer. The dry character of the periglacial zone, as established for central and east Europe (loess steppes, see p. 4), is due to this cause.

It may be mentioned that the fossil inland dunes of central Europe supply evidence for these east winds. That these dunes were built up on the sandy plains of large river valleys by east winds is shown by their shapes. They were subsequently worked over by westerly winds immediately prior to being fixed by vegetation (Solger, 1910).

(3) The anticyclonic winds were cold all the year round, since they came from an ice-cap the surface of which rose rather gradually towards the ice-centre.* In this respect they differed from anticyclonic winds in a temperate climate, which are cold in winter but warm in summer. The cooling effect of these winds on the periglacial zone must have been considerable; it is probably the cause of the low summer temperatures (generally less than 10° C. in July) which obtained in that zone (Zeuner, 1937).

(4) Since these cold and dry east winds prevented most of the depressions from entering the glaciated area and the periglacial zone, the amount of precipitation which reached such districts must have become less and less as the glacial climate became more intense. This factor must have brought about a complete change in the climatic character of that part of the periglacial zone which extended from west through central to east Europe. When the glacial phase began, the climate was pronouncedly oceanic in the west and centre, and in the east less continental than at present. As the ice-cap grew and the glacial anticyclone developed the climate became increasingly continental, with cold winters and with less precipitation, leading to a widespread replacement of forests by steppe and tundra.

It must not be assumed, however, that during the maximum of a glacial phase no depressions were ever able to enter the periglacial zone. While we have to think of winter conditions as comparatively stable and, therefore, intensely dry and cold, and while in summer the great pressure-gradient between the ice and the heated lands in the south must have resulted in a great outflow of heavy and cold air from the ice, making the summer climate of the periglacial zone windy, cold and dry, it is probable that in spring and autumn conditions were less settled, and depressions were now and then able to travel east along the southern edge of the ice-sheet. They would have helped to produce a luxuriant prairie vegetation in spring and in autumn would have supplied the snow cover for the winter.

CLIMATE OF PERIGLACIAL ZONE: SUMMARY.—During the height of a glacial phase, therefore, the annual cycle of the climate of the periglacial zone would have been something as follows:

Winter: Great cold, snow cover, albedo, comparatively quiet atmosphere.

Spring: Snow melting, precipitation, westerly winds, unstable weather. Luxuriant prairies spread over the country. Grazing mammals and their enemies populated the loess steppe.

Summer: Heating of soil by the rays of the sun, little precipitation, cold and dry ice-winds chiefly from N.E. July average below 10° C. Prairies dried up, loess dust deposited. The mammals retreated to the

* It is true, however, that both in Antarctica and Greenland, where the ice drops suddenly from high altitudes down to sea-level, relatively warm and dry winds are observed ("ice-föhn").

neighbourhood of the rivers and into the protected entries of the mountain valleys, where the vegetation now reached its climax. There the mammals also passed the winter.

Autumn: Decrease of temperature, fresh invasions of oceanic air, precipitation leading to snowfalls which bring the winter cover of snow.

Early winter: The ice-anticyclone spreads over the loess steppe (Zeuner, 1937, p. 388).

This sequence has been worked out in the present context as the probable result of the climatic changes which were set in motion in Europe by a phase of decreased summer and increased winter radiation. On the other hand, the biological aspects of the climatic conditions postulated have been amply confirmed by Pleistocene palæontology (Zeuner, 1937), and the buried soils have confirmed in detail the character of the climate of the periglacial zone (p. 17).

We are justified, therefore, in concluding that the entire climatic aspect of a glacial phase as observed in temperate Europe can be explained as the result of a period during which solar radiation was less in summer and more in winter than at present. The quantitative estimates have shown that fluctuations of this type, which have occurred repeatedly during the last million years as the result of the periodical changes of the perturbations of the earth's orbit, were sufficient to produce glaciations of the intensity observed, though much of the intensity has to be attributed to secondary effects. From the climatological point of view there is no objection to, but considerable support for, correlating summer minima of radiation with glacial phases.

Secondary Effects Outside the Areas of Glaciation.—The latitudes which were not directly affected by a glaciation experienced fluctutions of the radiation of the sun which were of the same type as those for the higher latitudes, though the rhythm changes as one approaches the equator. The fluctuations must have influenced the climate of the various zones of latitude, but their effects have not yet been worked out.

Superimposed on these primary fluctuations of the climate of the lower latitudes were the secondary effects produced by the glaciations of the higher latitudes. They, too, require elaboration. The nature of the modifications to be expected may be gathered from Brooks's useful book on 'Climate through the Ages' (1926, pp. 63, 315). It is unnecessary to pursue the subject further here.

The only zone for which sufficient material is available is the Mediterranean. Chapters VII and VIII will be devoted to it. Some general remarks concerning the tropics will be found in Chapter VIII also.

Drop in Sea-level.—Finally, another world-wide secondary effect of the glaciations must be referred to—the eustatic drop of the sea-level which accompanied each glacial phase. During the Last Glaciation it amounted to about 100 m. (see pp. 246, 251), and it was possibly as much as 200 m. during some of the earlier phases.

A drop of 100 m. may appear to be insignificant. It would, of course, have added this same amount to the depression of the snow-line and thus contributed to the intensification of the glaciation. But more important, probably, were the local changes in the coastlines. Much of the North Sea, for instance, would become dry land if the sea-level is depressed by 100 m.

and the British Isles would be joined to the Continent. This would mean a modification towards continentality in the climate of the areas concerned. One of the conspicuous results of this change was the extension of the loess steppe to northwest France and southern England.

E. PHENOMENON OF RETARDATION.

The notion that the maximum of a glaciation occurs later than the climatic event that caused it is an old one. If certain climatic conditions cause ice to accumulate in the feeding area of a glacier, it will take some time for this over-supply to reach the periphery, *i.e.* make the glacier advance. Wundt (1935), using observations on the Rhone Glacier by Mercanton, found that the winter minimum of temperature occurs in mid January, whilst the corresponding maximum advance of the ice front occurs on May 25 (mean of 20 years). Applying observations of this kind to the ice sheets of the Pleistocene, it is likely that the maximum of a glaciation occurred many years after the summer minimum of solar radiation which initiated it.

Radiation Minimum and Maximum Accumulation.—The first and perhaps most important factor of retardation affects the maximum accumulation of ice relative to the minimum of summer radiation that caused it. As explained earlier in this chapter, the great accumulation of ice on Scandinavia was due to a progressive self-intensification of favourable conditions, so that the accumulation of surplus ice in excess of the outflow must have continued for some time after the minimum summer radiation. The amount of this retardation cannot be assessed, though it was certainly not negligible.

Maximum Volume and Maximum Extension.—In considering the "maximum" of a glaciation it is necessary to make a clear distinction between the maximum of ice volume and the maximum extension of the ice-sheet. In recent years Blanc (1937) emphasized this distinction which was worked out by Hess (1904), who relied on work done during the last century by Forel, Finsterwalder and others.

The fact that glaciers continue to advance even after their volume has begun to decrease has an important bearing on the Pleistocene glaciations. It shows that the maximum extension, for which terminal moraines and other deposits supply the evidence, may have occurred some time after the maximum accumulation of ice in Scandinavia and the Baltic, although it is difficult to express this retardation in years.

The two factors of retardation discussed cause a lag of the maximum extension of the ice-sheet relative to the radiation minimum.

Retardation of Retreat.—A very different, and independent, phenomenon is the retardation of the retreat of the ice-front caused by the absorption of heat in the melting process.* It is well known that this amounts to 80 calories, sufficient to raise the temperature of the ice from about $-80°$ C. to $0°$ C., or of water from $0°$ C. to $+80°$ C. The melting heat is supplied by direct radiation and by air currents, and its absorption by the melting ice exerts a powerful cooling effect on its surroundings and slowed down the disappearance of the ice-sheet. Milankovitch (1930,

* This was appreciated as early as 1875 and 1885 by Croll, and in 1880 by Wallace. Croll (1885, p. 125) said: "This conservative tendency certainly renders it more difficult for the physical agencies to get rid of the ice during interglacial periods."

p. 161) paid special attention to this retardation factor and derived formulae for it. His calculations cannot be reproduced here. In applying them to the summer minimum of radiation which caused the first phase of the Last Glaciation, he found that the melting effect of the subsequent period of high summer radiation would not have removed more than 750 m. of ice. Since the thickness of the Scandinavian ice-sheet was probably greater than this, it is conceivable that some ice survived the following interstadial and gave a start to the second phase of the Last Glaciation (Milankovitch, 1930, p. 172).

Calculations of this kind are, of course, of the nature of estimates. But since two factors are active in causing the retardation of the maximum extension of the ice-sheet and a third in delaying its disappearance, at least two of which may be matters of many thousand years, it is necessary to pay serious attention to the phenomenon of retardation, and to consider the possibility that an unmelted residuum of a first phase helped the second phase of a glaciation on its way.

F. THE CAUSE OF AN ICE-AGE.

Astronomical Theory does not Provide the Cause of the Ice-Age.—The preceding discussion of the astronomical theory has, I hope, made it clear that the fluctuations of solar radiation, caused by the perturbations of the earth's orbit, provide a satisfactory explanation for the alternating glacial and interglacial phases. *They do not, however, explain the Ice-age as a whole.*

The perturbations fluctuated during the Tertiary in much the same manner as during the Pleistocene (though they cannot as yet be calculated), but they did not then cause glacial and interglacial phases. The reason for this can only be that a major oscillation of some unknown factor created conditions favourable for glaciation during the Pleistocene, but not for some considerable time before.*

A likely cause of the Pleistocene Ice-age, therefore, has been searched for by all modern workers on the astronomical theory.

Pole Migration.—The idea put forward by Köppen was that the poles of the earth were not stable, and that the North Pole moved into its present position during the course of the Quaternary, coming from the Pacific.† There is a fair amount of geological evidence for pole migration as such, but Köppen and Wegener's original conceptions (1924) were based on insufficient palæoclimatic evidence. As a result, their North Pole moved faster and faster towards the Present—an extremely unlikely postulate. Hence, pole migration found little favour with workers on the cause of the Pleistocene ice-age (Wundt, 1935), and Köppen himself reduced the fast movements suggested in 1924 (Köppen, 1930, 1933), though he continued to defend the curved route assigned by him to the pole during the Quaternary (Köppen, 1935). Milankovitch (1934, 1938*b*) calculated the movements of the poles on a geophysical basis, and arrived at a route dated in time units of unknown duration. By applying Kreichgauer's determination of the position of the Carboniferous North Pole and the age of this formation as determined by

* *Mutatis mutandis* the astronomical theory and the possible causes of an ice-age as treated in this context apply to the Permo-Carboniferous and other pre-Pleistocene glaciations also, but this matter is outside the scope of this book.

† This movement is purely relative, since the astronomical axis of the earth is considered stable, while the crust of the earth moves over the plastic core.

11

the radio-activity method, he obtained an estimate for the rate of displacement. His conclusion was definite: "This displacement proceeded extremely slowly in any case, so that it could not make itself felt during the last 600,000 years." "The displacements of the poles of the earth had no influence on the course of the Quaternary ice-age" (Milankovitch, 1938*b*, p. 688).

On quite independent lines Klute (1928), Woldstedt (1930) and Wundt (1935) came to a similar result, at least with respect to the Last Glaciation. The migration of the rotational poles of the earth, therefore, can safely be discarded as a possible cause of the Quaternary ice-age.

Continental Drift and Sea-currents.—A second movement which might have produced geographical changes of a character and magnitude sufficient to cause an ice-age is Continental Drift. The westward drift of America is the only one of the several postulated by Wegener (1937) which might have something to do with the Quaternary ice-age. Being parallel to the latitudinal belts, however, it would not have brought nearer to the pole any part of the area concerned, and it is necessary to invoke secondary factors, such as the cutting off from, or admission to, the Arctic Ocean of warm water from the Tropics. The theory thus becomes so highly conjectural that it is hardly worth pursuing: the individual rates of drifting of Greenland and North America are very different (if the available figures can be confirmed), the opening of the Atlantic gap would necessitate a closing of the Bering gap, the height of the submarine ridges plays a decisive part, and the influence of the warm sea currents would entirely depend on their quantity. It is not inconceivable that this type of change has something to do with the beginning of the Pleistocene ice-age, but it has a very slight factual basis.

The hypothesis of changing ocean currents influencing the climate of the higher latitudes has found great favour with v. Kerner-Marilaun (1930), and more recently Wundt (1935) has paid attention to it. Brooks (1926) discussed in detail the effects of changes in the oceanic circulation on the glaciation of the high latitudes.

Decrease of Solar Constant.—A very different possibility for the cause of an ice-age is the decrease of the energy output of the sun. The idea is very old in its original form. It has been revived in recent years, since the one factor which is regarded as constant in all varieties of the astronomical theory is the solar constant. Observations on sunspots have suggested that there may exist a fluctuation of the radiation sent forth by the sun, with a periodicity of thousands or even millions of years. This possibility cannot be denied, though to the best of my knowledge no proof has yet come forward.

A theory of the Ice-age based on a decrease of the solar constant, therefore, rests on an assumption which is possible but not supported by evidence. Assumptions of this kind have often resulted in the discovery of great truths and should not be discarded for *a priori* reasons, but rather be tested by comparing their obvious consequences with the evidence provided by nature.

A decrease of the solar constant at the end of the Tertiary would imply a reduction of the average temperature of the earth in the Quaternary. This idea looks very attractive. But difficulties arise, especially with regard to Tertiary climate, when the meteorological implications are considered. Brooks has paid special attention to the problem of the fluctua-

tions of the solar constant and discussed the various theories put forward (1926, pp. 96–114). He concludes that Huntington and Visher's theory (1922) of the correlation of sunspots and storminess of the climate, the most elaborate variety of the theory of changes of the solar constant, affords a possible explanation of the Ice-age, but that "it must be held in reserve while the effects of other factors whose variation is better known are studied."

FLUCTUATIONS OF SOLAR CONSTANT: SIMPSON'S THEORY.—In recent years, Sir George Simpson has developed an ingenious theory which is based on the assumption of two maxima of the solar constant during the Pleistocene. Though one is inclined to prefer known causes to unknown and unconfirmable ones, the possibility of two such oscillations having occurred during the Pleistocene is conceivable. If one accepts this premise of Simpson's theory, one has to admit that his subsequent arguments drawn from modern meteorology suggest a course of climatic changes which would explain the fourfold scheme of European glaciations as proposed by Penck about forty years ago. Briefly, Simpson's argument (1930, 1934, 1938, 1940) is as follows (Fig. 54):

(*a*) An increase of the solar constant produces a slight initial rise of temperature and, owing to increased convection in the atmosphere, greater cloudiness and increased precipitation.*

(*b*) Increased precipitation lowers the snow-line, and this results in a glaciation.

(*c*) "With continued increase of radiation the mean temperature will increase: the snowline will rise and" . . . "there will be a steady decrease in the area glaciated" (Simpson, 1940, p. 215).

(*d*) When radiation decreases, "the whole process is gone through in the reverse order" (Simpson, 1940, p. 215).

With two complete oscillations of the solar constant, one thus obtains a first group of two glaciations separated by a warm and wet interglacial, then a long interglacial which, solar radiation being at its minimum, is cold and dry, and a second group of two glaciations separated by a warm and wet interglacial. In the lower latitudes, where the glaciating effects are confined to the highest mountains, two pluvials only would have occurred, one corresponding to the first two glaciations, and the other to the second pair of glaciations.

These conclusions provide a chance for the testing of the theory by geological evidence. As regards the character of the interglacials, it has been found that the Last Interglacial which, on Simpson's theory, should have been warm and wet, was for some time pronouncedly continental, with chernozem forming as far west as the Rhine valley (p. 17). The Penultimate or Great Interglacial should have been cold and dry, but its climate, as shown by the Hötting deposit in the Austrian Alps (Penck, 1921), was about 2° C. warmer than at present, and probably somewhat more oceanic. Finally, the evidence for pluvials in the Mediterranean area (see Chapters VII and VIII) shows that there were more than two pluvials there, and the same is suggested for tropical and South Africa by recent investigations (p. 210). The theory of a double maximum of the solar constant, therefore, arrives at conclusions which contradict the geological evidence.

* This result is not generally accepted. See, for instance, Wundt (1933, p. 244), and Brooks's remarks on Blanford's theory (1926, p. 102). For a discussion of Simpson's theory, see also Köppen (1935).

Notwithstanding this lack of success of Simpson's theory of the Ice-age as a whole, it has made valuable contributions to the meteorological side of the problem, as shown in earlier parts of this chapter.

Theory of Eustatism.—There remains one other theory which deserves attention, the theory of eustatism. It has the advantages of being based on geological observations, of linking the phenomenon of ice-ages with other periodical phenomena of the earth's crust, and of suggesting the recurrence of ice-ages at long intervals.

One of the queer facts of Pleistocene stratigraphy is that the interglacial sea-levels were successively lower. Interpreted solely in terms of glacial eustasy, this would mean that in each interglacial less deglaciation took place than in the preceding one, an assumption which does not sound acceptable in view of the evidence for the climate of the interglacials. Some other factor, therefore, appears to have brought about the gradual lowering of the sea-level, the fluctuations due to glacial eustasy (p. 225) being merely superimposed on some major cause which depressed the sea-level progressively throughout the Pleistocene (see also p. 248). This movement was so regular that the major interglacial sea-levels, if plotted on the time-scale of the radiation curves, lie almost exactly in a straight line (Fig. 76, p. 250).

Now, this depression of the sea-level during the Pleistocene appears to be part of a process which has been operating throughout the Tertiary and possibly began in the Upper Cretaceous, when a transgression occurred on all continents, which was perhaps the greatest of all in the history of the earth (Gignoux, 1936; Umbgrove, 1939, p. 188). Baulig (1935) studied the Pliocene sea-levels and found the highest at 380 m. Deglaciation cannot provide the water for the sea-level to be at such a height, the maximum rise obtainable from this source being less than 100 m., so that alternative explanations have to be sought for.

The high sea-levels of the Tertiary are most easily interpreted by a subsequent upward movement of the land. That the land, or large portions of it, has risen in Cainozoic times has been proved in many places.

On the other hand, the ubiquity of the Pleistocene sea-levels, which are found at the same height in Australia and America as in Europe, suggests that the sea-level during the Pleistocene (and conceivably in the Tertiary also) actually became lower and lower, since it is impossible to regard the rising of the land as taking place at the same rate everywhere, so that the heights of ancient beaches remain the same in distant localities. It appears possible, therefore, that the sea-level sank by several hundred metres during the Tertiary and Pleistocene. The land would thus have been relatively elevated to greater heights, and a corresponding drop of the snow-line would have ensued.* This is the *theory of eustatism*, and the most probable cause of the phenomena interpreted by it is a sinking of the bottom of the sea.†

* It is of course true that erosion must have proceeded simultaneously with the crease in relief, but it could not have been uniform, and could not have prevented the mountain masses from being raised progressively to higher and higher altitudes relative to the sea-level.

† There is evidence for the sinking of the great ocean troughs, especially in the Pacific. It is only necessary to recall in this connection Darwin's theory of coral reefs (1889). For evidence obtained by more recent investigations, see Umbgrove (1939, p. 125), who says that "some deep ocean-basins must in all probability have originated in a recent geological past."

But it is apparent that, although eustatism (as distinct from glacial eustasy) seems indicated by the Pleistocene sea-levels, the sinking of the bottom of the sea necessitates compensatory upward movement of the land somewhere, because of the general tendency to isostatic adjustment in the crust of the earth. It is impossible, therefore, to separate eustatism and rising of the land sharply. This result is best expressed in Baulig's words (1935, p. 31): "Absolute shifts of the sea-level appear inexplicable except by deformation of the oceanic basins, which in turn implies changes in the absolute position of some at least of the lands. So that epeirogenic and isostatic movements on the one hand and eustatic movements on the other, far from excluding each other, appear correlative."

The theory of eustatism or sinking sea-level thus boils down to the conception that the crustal relief became intensified in the course of the Tertiary (see also Longwell, Knopf and Flint, 1939, p. 171; Thwaites, 1939, p. 108). It is easy to assume that, by the end of the Pliocene, sufficient areas had come to lie close to the snow-line for the fluctuations of solar radiation to become effective and to cause glacial phases.

In this connection it may well be thought significant that what knowledge we have of preceding ice-ages suggests that they also followed, or were contemporary with, great orogenetic epochs, and that they occurred during periods of exceptionally high crustal relief.

Many theories of rhythmic revolutions, or cycles, in the history of the earth have been put forward in recent years (Umbgrove, 1939) which intend to explain either the recurrent phases of intensified tectonic activity (for instance the theory of magmatic cycles, Holmes, 1926, 1937), or the cycles of transgression and regression of the sea (pulsation theory, Grabau, 1936, 1940), or a combination of both (Bucher, 1933; Baulig, 1935; Umbgrove, 1939). If the increase in crustal relief can eventually be established as the primary cause of ice-ages, these exceptional, though recurrent, periods would find a natural place in the major scheme of the geophysical evolution of the earth.

Conclusion.—It would lead too far to expound further the theory of eustatism in the present context, as it has no direct bearing on chronological problems. It may suffice to say that geological, palæontological and zoogeographical facts exist in abundance which appear to support it.

The conclusion to be drawn from this discussion of the possible causes of an ice-age is that no objection can be raised against the astronomical theory of the glacial and interglacial phases of the Pleistocene on the grounds that the latter does not explain the Pleistocene Ice-age as a whole. Several acceptable theories have been put forward to fill this gap, and the theory of eustatism appears to have a better chance of substantiation than the others.

We are now sufficiently prepared to enter upon a comparison of the geological divisions described in Chapters II to IV with the fluctuations postulated on the basis of the astronomical theory. This will constitute the test for the latter as a chronological system enabling us to date events in the Pleistocene in thousands of years.

CHAPTER VI

THE ABSOLUTE CHRONOLOGY OF THE PLEISTOCENE

A. THE CORRELATION OF THE GEOLOGICAL SEQUENCE WITH THE SEQUENCE OF FLUCTUATIONS OF SOLAR RADIATION.

THE possibility of dating in years the phases of the Pleistocene depends solely on the correlation of two sequences of events of independent derivation, the claim being that their resemblance is not fortuitous.

THE GEOLOGICAL SEQUENCE.—The first sequence is that of climatic phases derived from geological evidence. It has been discussed fully in Chapters II to IV. The summaries for the morainic areas of the Scandinavian and Alpine glaciations (Fig. 17), for the periglacial areas of central Europe (Fig. 24) and north France (Fig. 33), and for the morainic areas and the periglacial Thames Basin of Britain (Fig. 42), all agree in the following peculiar rhythm of glacial and temperate phases :

The Last Glaciation had three cold phases.

The Last Interglacial was much longer than the time elapsed since the Last Glaciation, and it was in part warmer than the Present.

The Penultimate Glaciation had two phases.

The Penultimate Interglacial was by far the longest, and in part warmer than the Present (" Great Interglacial ").

The Antepenultimate Glaciation had two phases.

The Antepenultimate Interglacial was temperate, much like the present-day climate.

The Early Glaciation had two phases.

There occurred several other cold phases before the Early Glaciation.

It hardly needs reiteration that this sequence cannot be observed in any one locality. Evidence for the phases following the Great Interglacial is plentiful, but scarce for those preceding it.

RELATIVE TIME-SCALE OF THE GEOLOGICAL SEQUENCE.—Several authors have attempted to design a relative time-scale for these phases of the Pleistocene, the basis for estimates of duration being the amount of erosion achieved by the rivers during the mild phases. Unfortunately we have no means of estimating the duration of the glacial phases since their intensity need not determine their duration. The earliest estimate is that by Penck and Brückner (Fig. 16) deduced from the erosion and the degree of weathering of the Alpine gravel-trains. It is perhaps the most valuable, since it was designed long before the publication of the first radiation curve. But it does not yet distinguish the phases of the four major glaciations (Fig. 55A).

Another estimate of relative duration was designed by Eberl (1930, pl. 2). He, too, used the amount of erosion achieved during the mild phases, in his area of Alpine gravel-trains north-east of Lake Constance (Fig. 55B).

A third estimate, by Soergel (1925), relies on the erosional differences between the terraces of the Ilm, in the periglacial area of the Scandinavian glaciation (Fig. 55c).

In Fig. 55 these three estimates are shown in their relative spacing, but the relative intensities of the glacial phases have been omitted, for the reason stated above. Considering the possibility of other factors interfering with the erosional activity of the rivers, the agreement between the three estimates must be considered as surprisingly good. They constitute the geological sequence which, by correlation with the astronomical sequence, enables us to date the Pleistocene.

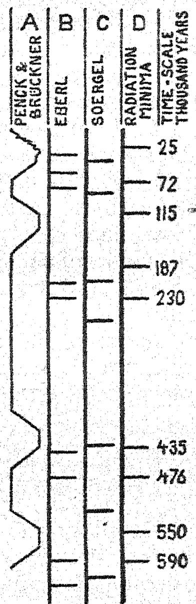


FIG. 55.—Diagram comparing three geological estimates of the relative duration of the climatic phases of the Pleistocene with the sequence of minima of summer radiation. Note that in Soergel's diagram the first phase of the first pair is not shown, being outside the picture.

THE ASTRONOMICAL SEQUENCE.—The "astronomical sequence" is, of course, the sequence of minima of summer radiation. For the purpose of its correlation with the geological sequence, the climatic interpretation of the radiation curves is irrelevant since, if it can be shown convincingly that the uninterpreted radiation curve closely resembles the geological sequence, it becomes highly probable that there is a causal connection between the two. If, on the other hand, we had to interpret or modify the radiation curve first in order to make it resemble the geological sequence, the probability of a causal connection between the two would be less. In fact, the untampered curve proves to be in close agreement with the geological sequence, so much so that we can safely conclude that the minima of summer radiation produced the glacial phases.

For this correlation it is advisable to select a curve which conceivably might have had a decisive influence on the intensity of the glacial phases. The most suitable appears to be that of 65° N., which is the latitude of northern Scandinavia, where the " centre " of the Scandinavian ice-sheets is to be sought. In Fig. 55 all minima of summer radiation exceeding an imaginary displacement of four degrees of latitude are entered in their chronological order.

Correlation of Geological and Astronomical Sequences.—A comparison of the three geological scales given, especially of Eberl's (Fig. 55B), with the minima of solar radiation suggests that the three summer minima of 25,000, 72,000 and 115,000* represent the Last Glaciation, those of 187,000 and 230,000 the Penultimate Glaciation, those of 435,000 and 476,000 the Antepenultimate Glaciation, and those of 550,000 and 590,000 the Early Glaciation. This correlation is in the first instance based on the length of the Penultimate and Last Interglacials, which is about 4 : 1 according to Penck, 2 : 1 on Eberl's scale, 1·5 : 1 on Soergel's scale, and 3 : 1 on the radiation scale. In the second instance it is based on the correspondence of the three minima R.M. 25, 72 and 115 with the group of three glacial phases included in the Last Glaciation. Compared with this, the earlier glaciations appear to have had two phases only, and these are most readily correlated with the pairs of radiation minima, R.M. 187 and 230 (=Penultimate Glaciation), R.M. 435 and 476 (=Antepenultimate Glaciation), R.M. 550 and 590 (=Early Glaciation).

This measure of agreement between the geological and astronomical sequences is not likely to be accidental. It affords, therefore, a reasonable basis for the transformation of our relative chronology of the Pleistocene into an absolute chronology.

B. ABSOLUTE CHRONOLOGY.

Retardation Neglected.—The adoption of the astronomical time-scale for the phases of the Pleistocene is easier than its application. It must be clearly understood that, in assigning the age of a minimum of summer radiation to a glacial phase, the phenomenon of retardation (p. 160) is neglected, and that the true age of the maximum of the glacial phase is somewhat less. Our present inability to assess retardation in years compels us to use the figures for the radiation minima. But since the retardation of the maximum of the third phase of the Last Glaciation was considerably less than 12,000 years, judging from de Geer's varve counts for the south Swedish moraines, it is evident that the error caused by the neglect of retardation is relatively small for the earlier phases.

The minima and maxima of summer radiation change their position on the time-scale slightly with the geographical latitude. Their amplitudes, however, vary considerably more. It is essential, therefore, that the radiation of the zone of latitude in which a locality is situated be duly considered. In the glaciated and periglacial areas, however, the influence of radiation changes experienced by higher latitudes was imposed on lower ones, so that it is permissible to use a selected curve as representative of a

* Henceforth, minima of summer radiation are cited in abbreviated form, viz. R.M. 25, R.M. 72, etc., dropping the Thousand years B.P.

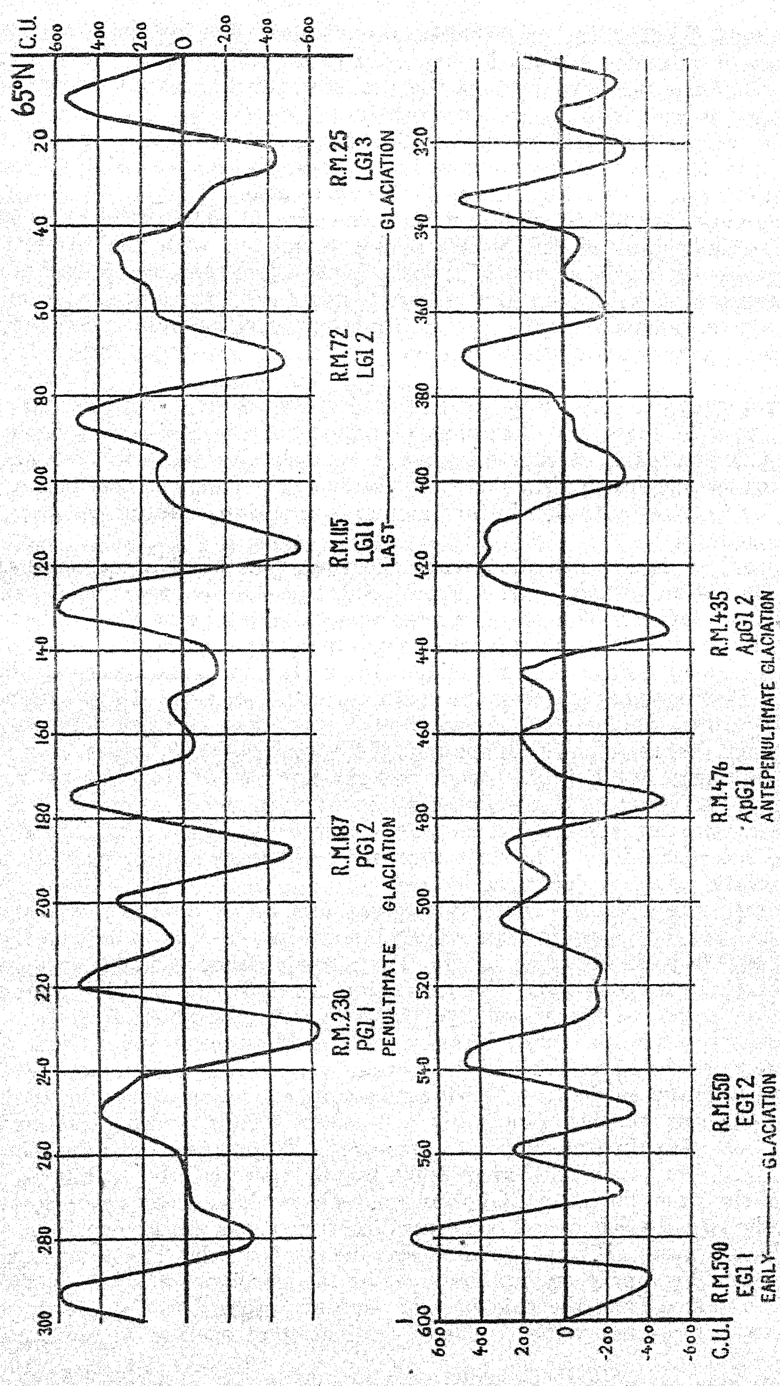


FIG. 56.—The detailed curve of solar radiation in summer, for 65° N. lat. Based on table in Milankovitch (1930). Scale in canonic units.

whole area of glaciation. For the Scandinavian area, for instance, the curve of summer radiation for 65° N. has been most widely used. This is the latitude of the northern part of the Scandinavian mountains, where the glaciating process is likely to have started.

The differences in the curves for 65°, 55° and 45° N. lat. (Fig. 52) are small and for most purposes insignificant, and the phases of the Alpine glaciations can be dated by means of this curve also.

The curve for 65° N., therefore, is given here in some detail (Fig. 56), with an indication of the glacial phases correlated with the respective minima, to serve for general reference. It should be used in preference to less accurate diagrams like Figs. 48 or 49, which give the amplitudes only, and these on a smaller scale. For latitudes other than those of temperate Europe, other curves given in this book should be consulted (Figs. 52, 67, 72, 73).

Comparison of Astronomical Dates with Geological Estimates of Time.—The ages and durations of periods of the Pleistocene derived from the astronomical time-scale agree remarkably well with estimates made on a geological basis. Since the absolute chronology as here proposed finds further substantiation in this manner, some of these estimates may be mentioned briefly.

According to the radiation scale, the time that has elapsed since the Last Glaciation, usually called Postglacial, must have been 25,000 years minus retardation. This space of time was estimated by de Geer at 18,000 years, by extrapolation from varve counts amounting to over 12,000 years (de Geer, 1926). From deposits of the Muota Delta in Lake Lucerne (which became ice-free some time after the maximum of LGl_3), Heim (1894) obtained 16,000 years. Steck (1892) found 20,000 years from similar deposits at Interlaken, between Lakes Brienz and Thun, and 14–15,000 years from the Aare Delta in Lake Brienz. Penck and Brückner (1909, p. 1169) assigned an age of 24,000 years to the Palæolithic station of the Schweizersbild near Schaffhausen, Switzerland, which was occupied during the third phase of the Würm Glaciation. The close agreement of these empirical values with the radiation date is highly significant.

For the interglacials, Penck's estimates, based on the depth of weathering and the intensity of erosion, were 60,000 years for the duration of the Last, and 240,000 years for that of the Penultimate Interglacial (Penck and Brückner, 1909, p. 1169). The corresponding intervals of high summer radiation lasted for 60,000 and 188,000 years respectively.

Estimates for the total duration of the Pleistocene suffer from the ambiguity of the lower limit of this period (see p. 174). If one accepts the Early Glaciation as the first Pleistocene event, relegating everything earlier to the Pliocene, the astronomical scale suggests 600,000 years. This figure is identical with the duration of the Ice-age in Penck's curve for the Alpine glaciations (Penck and Brückner, 1909, fig. 136; see this book, Fig. 16).

On the other hand, pre-Günzian cold phases have been made known from the Alps by Eberl and corresponding formations are known from the periglacial areas. If these phases are included in the Pleistocene, this period would comprise one million years on the astronomical scale. Rutten (1927) obtained from the thickness of deposits assigned to the Pleistocene of Java one million years. The determination of the age of radioactive

minerals of supposedly Pleistocene age also has yielded one million years (see, for instance, Holmes, 1915, p. 296).

Thus, the estimates of the absolute age of the Pleistocene and some of its phases agree so well with the absolute age assigned to them by means of the radiation curve, that they supply further evidence for the correctness of the Astronomical Theory in its modern form.

c. STRATIGRAPHICAL INTERPRETATION OF THE RADIATION CURVES.

METHOD OF APPROACH.—Several authors, having convinced themselves that the application of the fluctuations of solar radiation to the dating of the phases of the Pleistocene is essentially correct, have set themselves the task of comparing in detail the amplitudes of the curves with the geological evidence for oscillations of the climate.

The reader will be aware that this approach is directly opposite to that adopted in the present publication, since it assumes from the start that the radiation curves are applicable, and that the geological evidence must somehow be in agreement with them. In the present context no such assumption has been made; instead, it has been shown that the geological evidence results in a sequence of events which proves to match the sequence of minima of summer radiation. It is clear, however, that once one has convinced oneself by means of the approach adopted in this book, the other way promises to throw light on many unsolved problems. Some of these may be mentioned here, as examples of the type of constructive speculation which may be based on the Astronomical Theory.

GLACIATION CURVES.—Soergel (1937) undertook to construct a curve giving the state of glaciation at any one moment of the astronomical time-scale, for central Europe between 11° and 19° E. long. This *glaciation curve* (Soergel, 1937, pl. 1, also Zeuner, 1938, fig. 3) is regarded by Soergel himself as a first attempt to include the effects of solar radiation, caloric properties of the ice, retardation and other factors, in a single representation. The great value of this kind of work lies in the possibilities it affords for testing theoretical conclusions in nature. One of the striking features of Soergel's curve, for instance, is the short duration of the interglacials compared with the glacial episodes. Certain observations appear to me rather to point to a greater length of the interglacials and a short duration of the glacial phases.

The Older Loess is much more deeply weathered than the Younger Loess, so that the Last Interglacial appears to have been several times longer than the postglacial period of temperate climate. On the glaciation curve they are shown as of equal duration. Furthermore, it is inconceivable that the great platforms of marine erosion which characterize the interglacial sea-levels could have been cut in periods not exceeding 10,000 years.

A glaciation curve for the Swiss Alps was constructed by Beck (1938, fig. 2).

THE MINIMUM OF LGl_3.—Among the special problems arising from the application of the radiation curve, only a few can be pointed out here. An interesting one is the possible influence of the displacement of minima with geographical latitude. While the minimum of LGl_3 was attained 25,000 years B.P. on 65° N., the actual minimum of summer radiation on

55° N. and lower latitudes did not occur until 22,100 years B.P. This difference is slight, but it may have had some influence on the development of the peripheral part of the ice-sheet.

THE PROBLEM OF LGL_1 AND THE WARTHE PHASE.—A problem which cannot be settled with the evidence at present available is the identification of R.M. 115 in the Scandinavian area of glaciation. In the present context Soergel's view that this is the Warthe phase ("Würm I") has been adopted largely in order to simplify the representation of this extremely complex problem.

Evidence which implies that the Warthe phase may not correspond to R.M. 115 has been put forward chiefly by Danish authors (see p. 35 for references). In essence the Danish view is—

(1) That Warthe was an independent glaciation which extended to the west coast of Jutland, and—

(2) that the nature of the Herning interglacial series in Jutland shows that no ice-sheet ever passed over them, and that solifluction deposits which cover them correspond to the Weichsel phase.

The consequence of (1) and (2) together is that the Herning series must have been later than Warthe and earlier than Weichsel. In this case, the following three correlations with the radiation curve are conceivable :

(*a*) The first is that Warthe equals R.M. 115, the Herning series with its pronouncedly warm flora, and with the cool oscillation of the Danish Middle Bed, being placed in the interval between R.M. 115 and R.M. 72, where the radiation affords no explanation for the presence of the Danish Middle Bed. Furthermore, there are in the Herning series two separate phases with a climate decidedly warmer than the present, which would be difficult to explain by the course of the radiation curve between R.M. 115 and R.M. 72.

(*b*) On the other hand, one might maintain that Warthe is the small minimum at 145,000 B.P. and that the Danish Middle Bed equals R.M. 115. But this is unlikely because of the great intensity of R.M. 115 compared with the slightness of the Danish Middle Bed phase of cool climate which did not even produce solifluction.

Conversely, Warthe, a large phase, would be correlated with a relatively insignificant minimum.

(*c*) Thirdly, it is conceivable that Warthe equals R.M. 187, and that the Herning series is Last Interglacial, with the Danish Middle Bed representing the small R.M. 145. In this case, R.M. 115 or R.M. 72 would be unrepresented in the geological sequence (p. 52), presumably having produced an ice-sheet which was subsequently overridden. The view that the ice-sheet of R.M. 115 was overridden is held on other grounds by Grahmann, Dietrich and Knauer (for references, see pp. 39, 45).

Provided the Danish view is right, some variant of this third view which links Warthe with R.M. 187 would seem the most probable.

This raises the issue, Are the conclusions of the Danish geologists inescapable ? As to their second point that no ice-sheet passed over the Herning deposits, it would be unbecoming for one who has not himself examined these deposits to question the conclusions of the Danish experts. But in theory it does not seem entirely inconceivable that the condition of the Herning deposits might be compatible with an ice-sheet having passed over the locality.

As to their first point, however, that Warthe reached the west coast of Jutland, the evidence appears less conclusive. The extreme boundary of Warthe indeed looks as if receding eastwards north of the Elbe and merging apparently into the belt of young end-moraines which forms the backbone of Jutland Peninsula. Among these moraines, Warthe might still be identified one day. If this could be shown to be true, the Herning series sections would lie *outside* the Warthe moraine, and their undisturbed character and the absence of a covering moraine would find a satisfactory explanation. But the morainic deposits assigned to Warthe to the *west* of the Herning series sections, plainly could not be Warthe in this case.

It is here that, in my opinion, further research is capable of settling the problem. Are the morainic deposits in question, on Sylt for instance, Warthe, or perhaps Saale ? Counts of erratics are responsible for the present Danish view that Warthe did reach as far west as Sylt, but this method of counting erratics is still in the stage of controversy (p. 35). It is also conceivable that a retreat phase of Saale was characterized by erratics resembling those of the Warthe phase. It is not clear why successive glaciations should be distinguished in their erratics, but it is easy to understand that the composition of the " erratic index " depends on the size of the ice-sheet, certain ice-streams being more prominent in a small ice-sheet than in a large one.

If either of the two points of the Danish view proves to be erroneous, the most reasonable correlation of Warthe with the radiation curve would be that which, pending further evidence, has been adopted in this book, namely with R.M. 115.

It is hardly necessary to add that this local problem of detailed geological correlation does not affect the validity of the astronomical theory as a whole.

Can R.M. 25 be the Cause of the Weichsel Phase ?—The conception that in every glaciation the second phase must have been larger than the first, owing to retardation giving a start to the second phase (p. 161), has led Grahmann (1928) and others to believe that Warthe equals R.M. 72 and Weichsel R.M. 25. The Pomeranian phase would be degraded to an unimportant retreat phase not expressed in the radiation curve. Soergel (1937) has shown that this interpretation is highly improbable, one of his arguments being that the ice would not have had time to melt back to its present condition.

Phases of the Penultimate Glaciation.—A question related to that of the Warthe phase in Jutland is that of the relative size of the two phases of the Penultimate Glaciation. According to Soergel, Grahmann and Toepfer, PGl_2 was larger than PGl_1, and represents the Saale Glaciation. The new radiation curve, however, shows R.M. 230 to be so much larger than R.M. 187, that the suggestion made above in the discussion on the Jutland problem, alternative (c), that Saale equals R.M. 230 and Warthe R.M. 187, seems by no means impossible. This question could probably be settled in the area of periglacial river terraces. Toepfer (1933, p. 57) has put forward a number of arguments in favour of Saale being R.M. 187.

Minor Cool Phases.—The minor, yet fairly conspicuous minima of summer radiation which interrupt the interglacials (R.M. 145 in LIgl; R.M. 280, 305, 320, 360, 399 in PIgl) have been used repeatedly to explain interruptions observed in interglacial sections.

The claim that R.M. 145 caused an interruption of the Last Interglacial is comparatively sound, since it can be substantiated by the Danish Middle Bed, the oscillation separating the Main and Late Monastirian sea-levels (p. 251), the Glacial Terrace 4 of Thuringia and perhaps some other evidence. For each one of these pieces of evidence, however, alternative interpretations cannot entirely be ruled out.

In the Penultimate Interglacial, too, geological evidence points to at least two phases with a comparatively cool climate, for instance at Canstatt (p. 72), and in the Glacial Terrace 1 of Thuringia. But since the radiation curve affords five smaller minima to choose from, it is hard to say which might be represented by the geological evidence in particular localities.

D. THE PLIO-PLEISTOCENE BOUNDARY AND THE MAJOR DIVISIONS OF THE PLEISTOCENE.

The question of how to define the boundary between Pliocene and Pleistocene has occupied the minds of many geologists. It is impossible to discuss their views here, but it may not be out of place to investigate what contribution the absolute chronology can make towards the settlement of this practical problem.

PLIO-PLEISTOCENE BOUNDARY.—That the problem is one of practical delimitation and not one of finding a natural break which is applicable all over the earth will be obvious to all who have gone into this matter. The tectonic processes of the Pleistocene are the continuation of those obtaining during the Pliocene. The palæontological distinction by marine faunas is a conventional one, based on the percentage of Recent species in the deposits. That based on the appearance of certain terrestrial mammals, like *Equus*, *Elephas*, *Bos*, works well in restricted areas only (Pilgrim, 1944). The climatological distinction between Pliocene and Pleistocene which identifies the latter with the Ice-age and counts it from the " first glaciation " onwards has been badly shaken by the discovery of pre-Günzian glacial phases in the Alps and of corresponding cold aggradations in the periglacial areas.

One way out of the difficulty seemed to be to move the boundary back into the past sufficiently to include all the pre-Günzian cold phases, and also the transitional faunas like Perrier, Senèze, the earlier Crags. Eberl (1930) did so when he included the Donau phases (p. 43) in the Pleistocene, drawing the boundary at 800,000 years ago. In doing so he accepted a somewhat arbitrary radiation date, leaving two intense summer minima at 835 and 930,000 inside the Pliocene.

In earlier papers (Zeuner, 1935 ; 1938*a*, p. 54) I, too, advocated a shift of the boundary into the more distant past, suggesting the round figure of one million years B.P. as suitable. But I have since come to the conclusion that the advantages of such a procedure are outweighed by the practical difficulties it would cause in stratigraphical work. This boundary would include all the faunas of the transitional type, and all the *known* major summer minima of radiation, in the Pleistocene, but it would compel us to regard the Villafranchian and the Calabrian, *i.e.* the Upper Pliocene of current stratigraphy, as Pleistocene. This would cause considerable trouble with respect to the divisions of the Pliocene. Moreover, since we know

nothing about cold phases before one million B.P., this line of demarcation would be as artificial as any.

If, however, we cannot avoid adopting an artificial delimitation, it is best to choose one which necessitates the least number of changes in the conventional system of stratigraphy, and to define it by a feature which is not local, such as a radiation date. From the climatological standpoint it is possible to argue that, after all, the Early Glaciation of Europe is the first that left comparatively widespread evidence, and that the glacial succession of the great North American area also suggests that the first major glaciation there was roughly contemporary with Alpine Günz (p. 51). That these should be included in the Pleistocene is obvious, and all attempts to draw the boundary after the Early Glaciation or even the Antepenultimate Glaciation (Gams, 1935, for instance, adversely discussed by Girmounsky, 1932) are thus ruled out. I am now inclined to think that if one accepts a demarcation line just previous to the Early Glaciation, *i.e.* the radiation date of 600,000 B.P., the stratigraphical upheaval would indeed be small. In Europe, the Early Glaciation, the Red Crag, the St. Prest fauna (Pilgrim, 1944), the Milazzian sea-level (and part or the whole of the Sicilian ?) would be included in the Pleistocene, whilst the Villafranchian (Val d'Arno, Perrier) and the Calabrian would continue to form the upper Pliocene, as defined by Gignoux (1936, p. 584). Quite recently, a most valuable paper by the late Dr. Guy Pilgrim has appeared (1944), which treats of the lower limit of the Pleistocene in Europe and Asia. The boundary just outlined is proposed by Pilgrim on palæontological and geological grounds, and the faunal implications are discussed with such skill that I cannot but refer to his work for further information on this point.

As far as Europe is concerned, the only major uncertainty remaining is that of the position of the Sicilian. Since this question implies some familiarity with the Pleistocene sea-levels, it will be discussed in Chapter IX (p. 251).

Subdivisions of the Pleistocene.—If then this boundary is tentatively adopted, the Pleistocene can be subdivided very conveniently into three stages of about equal duration (200,000 years each) which are well marked palæontologically and delimited by climatic phases which, at any rate in Europe, are comparatively easy to identify (Zeuner, 1935, p. 372):

Upper Pleistocene.—Back to about 180,000 B.P.; Last Glaciation and Last Interglacial. *Elephas primigenius*, late *E. antiquus*, *Dama dama*, *Dicerorhinus merckii*, *Tichorhinus antiquitatis*, *Homo neanderthalensis*, *H. sapiens*.

Middle Pleistocene.—About 180,000 to 425,000 B.P.; Penultimate Glaciation and Penultimate Interglacial. *Elephas trogontherii*, *E. antiquus*, *Dama clactonianus*, *Dicerorhinus merckii*, *Homo* cf. *sapiens*.

Lower Pleistocene.—About 425,000 to 600,000 B.P.; Antepenultimate Glaciation, Antepenultimate Interglacial and Early Glaciation. *Elephas meridionalis*, primitive *E. trogontherii* and *E. antiquus*, *Dicerorhinus etruscus*, *Dama savini*, *Machairodus*, *Homo* (*Pithecanthropus*) *erectus* and *pekinensis*, *H. heidelbergensis*, *H.* (*Eoanthropus*) *dawsoni*.

This definition and these divisions of the Pleistocene are used in this book. The faunal characteristics may be gathered in greater detail from the last chapter (p. 258).

CHAPTER VII

CLIMATIC PHASES OF THE UPPER PLEISTOCENE IN THE COUNTRIES AROUND THE MEDITERRANEAN SEA

Though theoretically possible, the extension of the absolute chronology to zones other than the northern temperate zone encounters many difficulties. Differences in climate, absence of morainic evidence, relative scarcity of observations and, particularly, of sections studied in detail make any attempt at applying the astronomical method of dating to other climatic zones appear rather premature. It is not too early, however, to explore the territory even at the present stage of knowledge. This chapter, therefore, is of a somewhat preliminary character. It is confined to the Upper Pleistocene of the Mediterranean region, which is better known than that of other extra-temperate regions.

A. PLEISTOCENE DEPOSITS IN THE MEDITERRANEAN AREA.

Climatic Interpretation of Cave Deposits in the Mediterranean Region.—In the Mediterranean area, geological sections providing evidence for Pleistocene climatic fluctuations, and especially those containing implements or remains of early man, are often preserved in caves. Up to the present the climatic significance of cave sediments has been studied but little. Conclusions bearing on climatic changes and based on cave sections, therefore, rely usually on palæontological evidence.

Some kinds of sediments found in the Mediterranean caves, however, afford valuable additional information, and enable one in some cases to interpret sections without the aid of fossils.

The Mediterranean caves in question are mostly situated very close to the sea. Apart from less important deposits, they often contain one or several of the following sediments: (1) travertine layers, usually called *stalagmites*, or stalagmitic horizons, (2) various *cave-earths* of a more or less loamy nature, (3) coarser or finer rock-waste, or debris, often consolidated in the form of *breccias*, (4) transitions and combinations of these types, and (5) marine deposits.

Stalagmites.—For the formation of layers of calcium carbonate (travertines or stalagmites) a cave must be wet. In many caves horizons of stalagmite are found buried beneath other deposits, but no stalagmite is formed at the present day, dry and dusty cave-earth forming the surface. It is probable that in such caves the present-day conditions are too dry for the formation of stalagmites.

If fossil stalagmitic horizons are found in such caves and if one can prove that no great changes in the form of the cave have taken place, one is justified in concluding that at certain periods of the past the climate was moister than to-day. This applies, in particular, to the Grotte de l'Observatoire in Monaco, to several of the Grimaldi caves near Mentone, and to the Grotta Romanelli in Apulia.

There are, however, in the Mediterranean region caves which, even now, are moist enough for stalagmites to be formed. An example is the Grotta delle Capre in the Monte Circeo (Blanc, 1937*c*), in which the surface is formed by a layer of stalagmite containing Roman sherds.

CAVE-EARTH.—In most caves the surface-deposit is a loose cave-earth. The formation of this material does not appear to be taking place at present, since Upper Palæolithic implements are occasionally found in its top layers. This suggests that, under the present-day climatic conditions, nothing at all, or only a small amount of cave-earth, is deposited in caves of this kind.

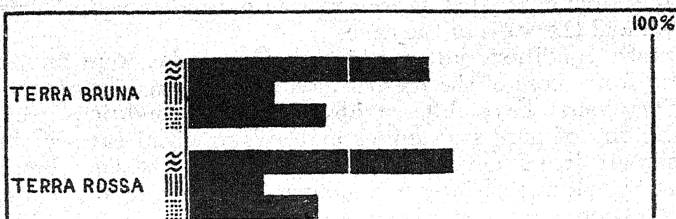


FIG. 57.—Mechanical analyses of Terra Rossa and basal bed of Terra Bruna from the Grotta Romanelli, Apulia. For signs, see Fig. 26.

The origin of the cave-earth varies. There are, for instance, layers which consist more or less exclusively of bat-guano and other organic detritus. Whilst in the temperate regions of Europe such layers indicate a mild climate rather than a cold one, they are of little climatic import in the Mediterranean. Inorganic cave-earths, on the other hand, contain always a fair amount of colloidal matter, *i.e.* they are loamy. This suggests that their material is, at least partially, the product of chemical weathering. Since the shape of most caves has suffered comparatively little alteration since they were carved out by the sea, and since the deposits of cave-earth are often too thick to be the result of local weathering inside the cave, the material composing the cave-earths is likely to have come from outside the caves, where plenty of weathering-loam is available in surface-soils of brown-earth or red-earth types. Transport into the caves was effected either by water or by wind, as indicated by the structure of some of the Mediterranean cave-earths.

As to the eolian origin of certain cave-earths, an instructive example is provided by the Grotta Romanelli in Apulia. Its layers of " Terra Rossa " and " Terra Bruna " contain abundant grains of a fine sand with all the characteristics of a wind-blown sand (G. A. Blanc, 1921). Blanc concluded that the climate during the deposition of these layers must have been dry and desert-like. The latter term is, perhaps, too extreme, since sand and dust are carried by wind in areas which are far from being deserts, though

always open and practically devoid of forests. Mechanical analysis of the cave-earths of the Grotta Romanelli (Fig. 57) shows that the sand grade consists chiefly of wind-blown sand as described by G. A. Blanc, but the grading of the material as a whole is not that of a wind-blown dust, or loess. The reason for this is to be found in its derivation from superficial weathering-loams, the particles of which are disintegrated in the process of analysis. Moreover, the very loose texture of the Romanelli and other cave-earths renders an eolian mode of deposition extremely probable. Had they been laid down under water, they would have formed a dense loam. Such denser deposits are, in fact, known also.

Breccias.—The term "breccia" is here used in the widest sense, including unconsolidated deposits of angular rock-waste. Breccias are striking formations in some of the caves. They are often found in well-defined layers, and consist almost exclusively of angular pieces of rock identical with the rock in which the cave is situated. Since no or nearly no wear is observed on the pieces, transport must have been almost negligible. It is probable, therefore, that these breccias consist of material detached from the roof and the walls of the cave.

The climatic conditions under which these breccias were formed must have differed from those of the present day, since no breccias are now being formed. They must have differed also from the conditions responsible for the formation of pure stalagmites and *well*-stratified cave-earths, since such deposits are free from breccious components. Yet some breccias are consolidated by calcareous sinter in a manner which can hardly be explained by *later* infiltration.

More frequently, breccias are embedded in loose cave-earth of possibly eolian origin, where single detached blocks or smaller pieces are also often encountered. G. A. Blanc (1921, 1930), therefore, holds the view that angular rock-waste, as typically represented in the Grotta Romanelli in Apulia, was formed by the mechanical ("thermoclastic") action of frost. This is, indeed, the only suggestion which is well corroborated by palæontological and geological evidence. Where, in the "terra bruna" of the Grotta Romanelli, rock-waste becomes frequent, the fauna turns cold (*Alca impennis*, for instance). In the Grotte du Prince, the fauna presents a cold character (reindeer) where the large blocks appear, and similar conditions may be observed in the Grotte de l'Observatoire.

There is, however, a much rarer type of breccious deposit, which is produced by the sea destroying the faces of cliffs. Such breccias are sometimes found resting on, or interstratified with, beds of beach pebbles.

The question of the consolidation of breccias, either more or less simultaneously with their formation, or subsequently, is as difficult to settle as it is important. Both cases certainly occur, and they require different climatic interpretations, to be arrived at by an investigation of the respective localities.

A special problem is presented by the screes of consolidated breccia which often cover the slopes. Since they sometimes extend to below sea-level and often appear to have done so previous to the cutting of cliffs by the present sea-level, they are likely to have been formed in phases of low sea-level. This would imply contemporaneity with glacial phases and, therefore, a cool fauna. It would be necessary, and worth while, to evolve

a technique of recovering faunal remains in a tolerable state of preservation from these breccias.

Marine Cave Deposits.—Finally, marine pebble-gravels and sands have to be mentioned as occurring in Mediterranean caves. Petrologically and palæontologically they are easy to recognize. More will have to be said about this kind of deposit in connection with ancient sea-levels (Chapter IX). In the Mediterranean, their fauna is, as a rule, of a warm character, and they usually are found at the base of the series of cave deposits.

Mediterranean Cave Deposits: Summary.—Although the climatic interpretation of cave sediments is by no means always conclusive, it is often true that—

(a) Loose, unstratified cave-earths indicate wind-action (arid climate),

(b) loose rock-waste or breccias indicate thermoclastic weathering, mostly in a frost-climate;

(c) well-stratified cave-earths indicate the presence of running water;

(d) stalagmitic floors indicate humid conditions;

(e) absence of deposits indicates a climate like that of the present Mediterranean.

In considering these rough-and-ready rules it must be kept in mind that the shape of the cave influences the deposits. Some open caves are always "dry," some long and deep caves always "wet"; only the intermediate type is sensitive to climatic fluctuations. Fortunately a great number of this intermediate type exist.

B. IMPORTANT UPPER PLEISTOCENE SECTIONS OF THE RIVIERA AND ITALY.

In the following paragraphs a few well-investigated sections of the Mediterranean region will be discussed in some detail, with a view to discerning climatic fluctuations which occurred during the upper Pleistocene. The fluctuations of the sea-level will here be mentioned in passing only, since they are the subject of Chapter IX. The arrangement of the localities is roughly geographical, beginning with the Italo-French Riviera, going south to South Italy, thence to Palestine, and finally to Spain.

Grotte de l'Observatoire, Monaco.—The Grotte de l'Observatoire at Monaco (Boule, 1927; Verneau, 1933) is not a sea-cave. It is of great archæological interest and mentioned here because, with its four stalagmitic levels, it suggests four humid phases. They are separated by cave-earths, and covered by an uppermost cave-earth with a reindeer-fauna. At least the last humid phase of this cave, therefore, was followed by a dry-cold phase.

Grimaldi Caves.—The famous caves of Grimaldi lie on the Italo-French Riviera, near Mentone, only eight miles east of Monaco. They are quite close to the sea, at a locality known as "red rocks," Rochers Rouges in French, Baoussé-Roussé in Provençal, Balzi Rossi in Italian.

Excavations were carried out by Rivière as early as 1874. He dug in the uppermost beds only, but his discovery of human skeletons made the caves famous. The most important excavations were carried out early in

the present century by Prince Albert I of Monaco. The results were described in an imposing monograph by Boule, Cartailhac, Verneau and de Villeneuve (1919). In recent years the Italian Istituto di Paleontologia Umana has taken up this work again and obtained results which have not yet been published in detail (Graziosi, 1937) but promise to be most important.

The Grimaldi caves, which all lie within a few yards of each other, were carved out by the sea during the high-level phase of the Monastirian, which is the equivalent of the Last Interglacial of northern Europe (see p. 249). The well-known beach deposits with *Strombus bubonius* of this phase were found in the Grotte du Prince at about 9–11 m. above sea-level, and a seam of bore-holes of the bivalve shell *Lithodomus* at 22·70 m. indicates the height of the sea-level when the cave was hollowed out. This height is that of the *early* or Main Monastirian sea, so that this cave at least must have been

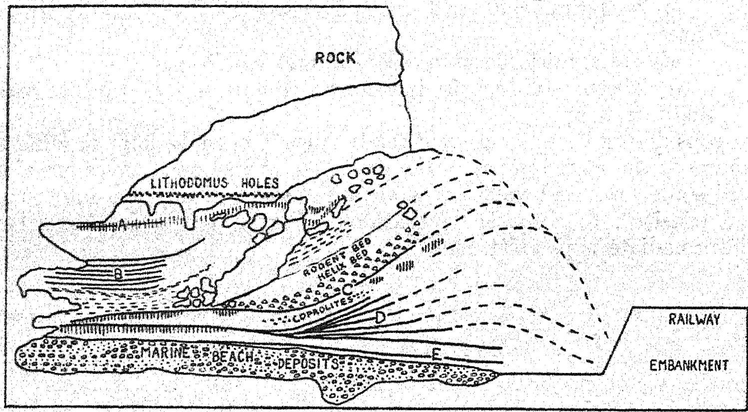


FIG. 58.—Section of the Grotte du Prince, Mentone. Based on Boule (1906, p. 254). A to E, occupation levels. Vertical hatching, stalagmitic horizons.

dry during the latter part of the Last Interglacial (Late Monastirian 7·5 m. sea-level).

The beach-deposits are still accessible in the cave called Barma Grande, where they were exposed by the excavations of the Istituto di Paleontologia Umana (Graziosi 1937). They consist of rounded pebbles, many of them very coarse, mixed with smaller ones and with sand, and rich in marine shells. Among these, the gastropod, *Strombus bubonius*, is remarkable for its absence from the present Mediterranean; it is now restricted to the tropical coast of Senegal. Its presence in the Monastirian sea may be taken as a sign of warm conditions (see also p. 232).

GROTTE DU PRINCE.—In the Grotte du Prince, as well as in the Barma Grande, the *Strombus*-beach deposits are covered by a sterile layer of sandy gravel on which rests immediately the first Palæolithic horizon (E of Grotte du Prince, Fig. 58), which has yielded *Hippopotamus, Elephas antiquus* and *Dicerorhinus merckii*. From this bed upwards, a detrital cone was developed in the entrance of the Grotte du Prince, consisting of debris falling down the

vertical wall * into which the cave is cut. This cone, and the cave-floor behind it, contain a number of occupation levels with *Elephas antiquus* and *Dicerorhinus merckii*, accompanied by a few specimens of ibex. *Hippopotamus* is no longer found, and the appearance of the ibex instead may be interpreted as indicating that the climate had become slightly cooler than it was during the beginning of the marine regression. The remaining fauna strongly suggests that this change was very slight indeed and that the climate was by no means cold.

A marked deterioration of the climate, however, is apparent in the top layers of the cone, where very large blocks occur. The Palæolithic layers are no longer *on* the cone, but in a protected position *behind* it (Foyer B). The fauna now includes reindeer, *numerous* ibex, and the marmot. In the uppermost Palæolithic horizon (A), finally, ibex and *Elephas* (*? primigenius*) are found.

Whilst there is no clear geological evidence for a climatic change, because of the detrital origin of the entire cone and the almost permanent presence of dripping water which partly consolidated the beds, the palæontological evidence just outlined shows convincingly that the warm Monastirian sea receded, to be followed by a temperate period which, in turn, was replaced by a distinctly cold phase.

The absence of later deposits in the Grotte du Prince is due to the fact that this cave was filled with debris during the cold phase indicated in the top layers of the cone.

OTHER IMPORTANT DEPOSITS AT GRIMALDI.—The succession is continued in the neighbouring Grotte des Enfants (Grotta dei Fanciulli), named after the skeletons of two children of *Homo sapiens* found by Rivière. This excavator stopped at a hard layer which he believed to be the floor of the cave, but recent excavations (Graziosi, 1937) proved this to be a stalagmite beneath which the section continued.

Graziosi says that the fauna below this stalagmite was cold. It can be correlated with the top of the section of the Grotte du Prince. Above the stalagmite the fauna is mild again (*D. merckii*, *teste* Obermaier, 1937*a*). Higher horizons contain wild boar, red deer, roe deer, wolf and hyena; the only species which might, though need not, point to cooler conditions being *Ursus spelæus*, *Capra ibex* and horse. In the top portion of the section the fauna is distinctly colder, however, since ibex and reindeer become frequent.

Two cold phases are thus suggested.

Since it is known from the Grotte du Prince that this whole succession is later than the *Strombus*-beach of the Last Interglacial, the two cold phases of the Grimaldi caves appear to be the equivalents of the two major phases of the Last Glaciation of northern Europe.

Furthermore, the combined succession of the Grotte du Prince and the Grotte des Enfants suggests the correlation of the two upper stalagmites of the Grotte de l'Observatoire with the two major phases of the Last Glaciation. The difference in the kind of deposits formed at Grimaldi and Monaco respectively may be due to the difference in the character of the

* The cone was removed during the excavation, but a new one has since begun to form. This time, it is made up of detritus from a hotel on top of the cliff, so that this important site is being deplorably contaminated.

caves. Yet, the uppermost cave-earth in the Grotte de l'Observatoire with its component of large blocks is much like the corresponding deposits in the Grimaldi caves, so that the Grotte de l'Observatoire appears to suggest that at least the second phase of the Last Glaciation produced first a humid stalagmite and then a drier, cold-temperate, cave-earth. It will be seen later on that this faint suggestion can be substantiated elsewhere and assumes considerable climatic importance.

Riparo Mochi.—Against the correlation of the two humid phases observed in the caves with the first and second phases of the Last Glaciation the objection may be raised that they could equally well represent the second and third. A set of new sections, discovered by A. C. Blanc in 1938 (Blanc, 1938), however, disproves this alternative.

The new site is situated about halfway between the Grotte des Enfants and the Grotte du Prince, more precisely between two smaller caves called Grotte de Florestan and Grotte du Cavillon. It is merely a shelter, not a cave, and the deposits are cut by the railway line which runs parallel to the rock-wall. The locality was named "Riparo Mochi" by Blanc.

The deposits of the Riparo Mochi are the youngest preserved at Grimaldi. They consist mostly of loose debris, but are interrupted by a limestone breccia cemented by stalagmites in certain places. This may be taken as an indication of a somewhat damper phase which intervened in the formation of the loose debris. Since humid phases, in the Mediterranean, signify cooler summers, it is not impossible that this stalagmite of the Riparo Mochi dates from a third and apparently last cool phase.

Riviera Caves: Summary.—The climatic succession of the Riviera caves thus appears to have been somewhat as follows:

Loose debris of Riparo Mochi.	
Stalagmite of Riparo Mochi	? LGl_3.
Loose debris of Riparo Mochi.	
Top strata of Grotte des Enfants (cold fauna) .	? LGl_2.
Main deposit of Grotte des Enfants (mild fauna) .	interstadial.
Deposit below stalagmitic floor of Grotte des Enfants (cold fauna) = top of cone, Grotte du Prince .	LGl_1.
Lower part of cone, Grotte du Prince (mild fauna) .	late LIgl.
Monastirian sea, Grotte du Prince	LIgl.

A correlation, purely tentative for the moment, is added. It suggests that two phases of the Last Glaciation are represented by cold faunas. The third phase is possibly indicated by the stalagmite in the Riparo Mochi. It will be seen that this sequence can be substantiated and further elaborated in other parts of the Mediterranean. For the time being it may serve as a guide on our way to a better-established succession.

Lower Versilia.—The Lower Versilia is a coastal plain lying at the foot of the part of the Appennines called the Apuan Alps, on the east side of northern Italy between La Spezia and Leghorn. It is about 60 km. long and, in its most important part between Viareggio and Pisa, 8 km. wide. There is a very flat sandy beach-ridge running along the coast, and behind it peaty marshes which are replacing a lagoon of which only a lake remains, the Lago di Massaciuccoli (diameter about 2·5 km.). At this lake sand is extracted on a large scale by pumping and dredging from below water-level, and the stratigraphical evidence provided by these activities, combined

with the results of a number of borings for freshwater, have enabled A. C. Blanc to compile a most remarkable series of deposits (Blanc, 1935*a*, 1936*a*, *b*, 1937*a*, *b*). The peats and macroscopical plant-remains were studied by Tongiorgi (1936, 1937), and by Marchetti and Tongiorgi (1937). Down to about 26 m. below sea-level, the evidence is mainly provided by the sand-extraction plant at the Lago di Massaciuccoli ; thence down to 95 m. below sea-level by borings only.

The succession of the strata, beginning with the earliest, is as follows (Fig. 59) :

A. At the lowest levels, at and below – 90 m., a marine sand occurs, corresponding to a sea-level of about 90 to 100 m. lower than the present. Its fauna contains only species still living to-day. No list of species has yet been published.

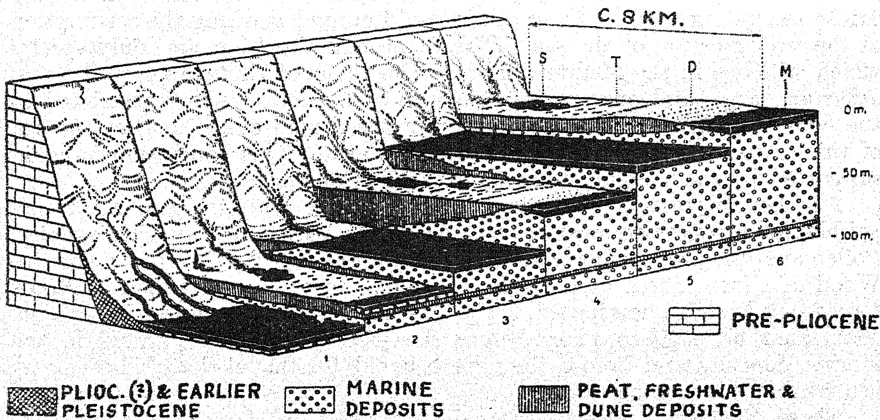


FIG. 59.—Development of the coastal plain of the Lower Versilia according to A. C. Blanc (1935). For stages compare text.
1. Stage A. 2. Stage B. 3. Stage C. 4. Stage D (regression of sea not clearly shown). 5. Stage E. 6. Stages F and G (regression not clearly shown). S. Lago di Massaciuccoli. T. Peat marsh. D. Coastal dune. M. Sea.

B. From about – 90 to – 76 m., sands with terrestrial and freshwater mollusca occur. No list of the fauna has been published.

C. From – 76 to – 61 m. a second marine series contains seeds of the vine (*Vitis vinifera* L.), which indicate that at that time the climate was mild. Since this complex is found all over the area, the marine transgression appears to have reached to the foot of the mountains.

D. This period was followed by one of temporary regression of the sea. Peaty sands and layers of peat, encountered at depths from – 68 to – 30 m., were formed behind a seaward belt of sand which prevented the sea water from entering the lacustrine region. The conditions then were essentially similar to those prevailing to-day. It is, of course, impossible to estimate the amount of the recession of the sea, whether it was merely a temporary halt or very slight oscillation (this is Blanc's view), or whether it was a substantial regression, though in intensity and duration less con-

siderable than that of phase A. The clays and peats of phase D (called the "lower peat") testify to a cool climate, which becomes more marked as one proceeds from the bottom to the top. In the lowest horizons, oak forest still dominates according to Marchetti and Tongiorgi; in the middle horizons oak is replaced by fir (*Abies*) and pine in about equal proportion. This signifies a cool but fairly humid climate. In the upper horizons 90 per cent. of the pollen belongs to *Pinus mugo* (= *montana*) and *Pinus silvestris*; there is no doubt that the climate had by this time become cool and continental. This cold phase, therefore, began with a humid climate and ended with a continental one, a change which finds a parallel in the Grimaldian cave-earth with evidence of a frost climate, preceded by a humid stalagmite. The significance of this combination will be discussed later on.

E. The lower peat complex is covered by another series of marine sands, extending from − 30 to about − 12 m. and marking the resumption of the transgression of the sea. The fauna contained includes only species which still live in the Mediterranean. The shells of *Pectunculus* and *Spondylus* are large, and one species, *Purpura haemastoma*, is now restricted to the coast of Algeria. It is evident from the faunal evidence that the sea of this transgressive phase was decidedly warm. This conclusion is again supported by the presence of seeds of *Vitis vinifera*.

Another interesting component of the marine *Purpura*-beds are rolled pebbles of compressed peat. They are often perforated by *Pholas*-holes. Pollen analysis proved their identity with the top layers of the lower peat, D. Wood of *Pinus*, *Picea* and *Betula* was found in them and pollen of *Pinus* (*mugo* + *silvestris*) dominated. The fossilization and compression of the peat must have taken place before the pieces were incorporated in the marine deposits and before they were bored by the pholads, whose holes are perfectly uncompressed.

These *Purpura*-sands are the chief object of the large sand-extraction industry established at the Lago di Massaciuccoli.

F. The marine *Purpura*-sands are covered by sands of a terrestrial character, varying in thickness from 5 to about 12 m. (*i.e.* from about − 15 to − 12 m. up to − 7 m. and in places up to present sea-level). They contain wind-worn pebbles, and when the extraction pipes of the pumping branches lie at the level of − 12 to − 14 m., they suck up Palaeolithic implements in fairly large numbers. Relying on signs of wind-action on some of the implements, Blanc suggests that they come from an eolian pebble horizon at a depth of about − 7 m.

G. The partly eolian sands of phase F are thickest near the coast, and the depression thus formed is filled with peat. Underlying this peat (H, *infra*) lacustrine clays are found locally, notably near the south-east side of the Lago di Massaciuccoli, resting directly on *Purpura*-sands at an average level of about − 6 m. (Tongiorgi, 1936). Their pollen-contents, examined by Tongiorgi, show that pine and fir are present in about equal proportion, and he concludes that the climate was "cold and moderately oceanic."

The stratigraphical relation of these lacustrine clays to the sands of F is not clear. Lumps of the clay are extracted by the pumps simultaneously with the sands of phase F. Blanc (1937*a*, p. 638) appears to regard the formation of F as in part contemporaneous with the deposition of the

lacustrine clay, G. Since the clay is not found below − 7 m., whilst the sand reaches down to − 12 to − 15 m., at least a portion of the sands, F, is likely to antedate the formation of G. It will be necessary to return to this point later on.

H. The lacustrine clay is covered by peat, from − 7 m. up to + 1 m. In many places the peat is thinner than this. At the west side of the Lago di Massaciuccoli, for instance, there is only about 1 m. of peat. Pollen-analysis and macroscopical study of the flora and fauna prove that this peat was formed under climatic conditions resembling those of the present day, and the formation of this peat would still continue if artificial drainage had not interfered with it.

INTERPRETATION OF THE VERSILIA SECTION.—The section of the Lower Versilia is important for its evidence of climatic oscillations and of eustatic fluctuations of the sea-level.

Its chronological frame is given by the upper peat, H, which links it with the present, and by the marine fauna of the lowest deposit, A, which, according to Blanc, contains no typically Tyrrhenian species (see p. 232) but only Recent ones and, therefore, must be later than all the phases of the Mediterranean sea containing the Tyrrhenian fauna, namely, the Tyrrhenian *sensu stricto*, plus the Main and Late Monastirian high-sea-level phases.

Furthermore, since the marine phase A, at 90 or more metres below the present sea-level, was followed by a terrestrial phase, B, A represents the deposit of the lowest observable stage in the recession of the sea, and B was deposited as the water receded from A. The sea-level at that time must have been lower than − 90 m. Since this regression post-dates the Monastirian beaches of the Last Interglacial (see p. 249), it has with good reason been regarded by Blanc and others as the result of the eustatic withdrawal of water from the oceans during the Last Glaciation.

It is necessary to assume, therefore, that the beds A + B correspond to a glacial phase of the Last Glaciation. Since the later deposits of the Versilia series contain evidence of two other cold phases (beds D and G), the tripartition of the Last Glaciation, so evident in temperate Europe, and vaguely suggested by the Grimaldi caves, appears to be confirmed for the Mediterranean zone by the Versilia section.

Even the relative intensity of the two later phases is the same in both areas, the third being less intense than the second; and if Blanc's view, that the low sea-level of phase A + B was never reached again, can be substantiated (and there is no reason against it), the greatest amount of water would have been withdrawn from the ocean during the first of the three cold phases. In other words, this would correspond to the first phase of the Last Glaciation, which is held to have been the largest.

This correlation of the three cold phases of the Versilia may be accepted as probably correct in its outline. We shall see later on to what extent a chronological displacement exists between the humid, or pluvial, phases of the Mediterranean and the glacial phases of temperate Europe (p. 203), but for the present this question may be postponed.

An interesting problem is that of the heights attained by the sea-level during the six climatic phases which can be distinguished. Of these, only the first (more than − 90 m.) and the last (modern sea-level) are known to us so far. The whole series cannot, however, represent one continuous

transgression since, although it extended twice to the foot of the mountains (phases C and E), it was driven back twice at least to the edge of the coastal plain (phases D and F). Whilst Blanc regards these latter phases as minor oscillations, slight recessions or halts, there seems to me no clear evidence for their slightness. On both occasions the sea-level can have dropped considerably without affecting the character of the preserved deposits. One thus finds that during phase C the sea-level reached at least − 60 m. and was possibly much higher, and during phase E at least − 12 m. and possibly more, whilst during phase D it dropped to below − 60 m. and during phase F to below, possibly much below, − 12 m. The figures derived from the deposits thus give no more than *minimum* values for the oscillations of the sea-level.

VERSILIA SUCCESSION: SUMMARY.—In view of the general importance of the Versilia section, the sequence of events may now be summarized:

A. The sea-level at − 90 m., receding still further, leaves behind deposits with shells on the submarine platform.

B. As (A) proceeds, terrestrial and freshwater deposits spread over the exposed marine deposits. First phase of the Last Glaciation.

C. The sea rises again, overwhelms the terrestrial deposits of (B) and extends to the foot of the mountains. Maximum sea-level of this phase at least − 60 m., possibly higher. Climate mild. Interstadial LGl_1/LGl_2.

During the later part of this phase the rate of rise of the sea-level appears to have slowed down, and a beach-ridge with peaty marsh behind it developed (early part of D).

D. The conditions just described continue, but the sea-level begins once more to drop, the climate becomes first cool and humid, later cold and continental. Sea-level drops by an unknown amount. Second phase of the Last Glaciation.

E. The sea-level rises again, at least up to − 12 m. and transgresses the beach-ridge and peat of D, destroying a portion of the earlier deposits and eventually reaching the foot of the mountains. Climate again mild. Interstadial LGl_2/LGl_3.

F. A new recession begins, and as the sea retreats, exposing the surface of the deposits (E), terrestrial sands are laid down, probably in the shape of beach-ridges and dunes.

G. Behind the deposits of (F) freshwater is ponded up while the climate turns cool and humid and the sea-level is low. Third phase of the Last Glaciation.

H. The sea-level rises again, finally to gain its present height. New beach deposits and dunes are added to, and mixed with, those of (F), producing the flat, sandy ridge which at the present prevents the sea from flooding the marshes lying behind the ridge. Peat is formed in the marshes and the climate resembles that of to-day.

THE PONTINE MARSHES.—The Pontine Marshes, a district about 50 km. south of Rome, is by virtue of its associations with Roman history generally known. It is however less known that this district has become one of the most important areas for Pleistocene research in Italy, in consequence of extensive drainage operations carried out in recent years. Again we owe to A. C. Blanc a survey of the available sections (Blanc, 1935*b*, 1936*a*, *c*, 1937*d*).

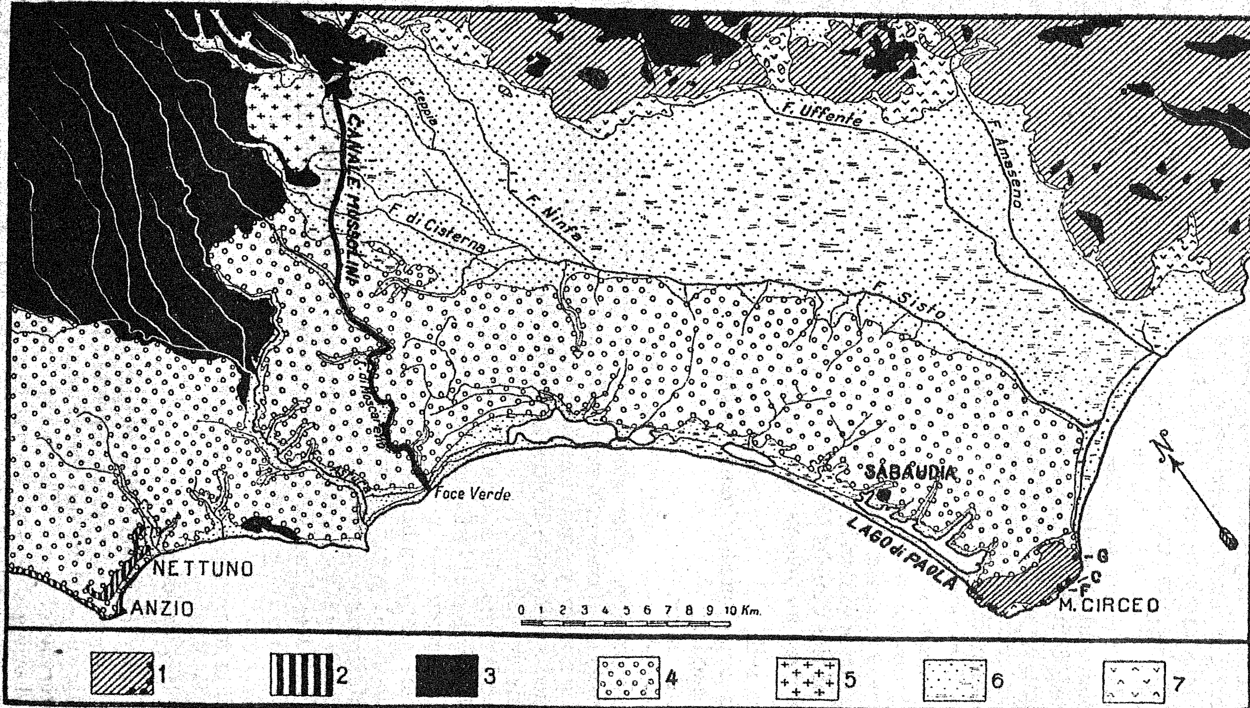


FIG. 60.—Plan of the Pontine Marshes before the drainage operations, after A. C. Blanc (1937*a*), reproduced by permission of the Geological Society of London. Canale Mussolini and some localities added.

1. Limestone of Monte Circeo, with some of the caves carved during the Late Monastirian phase. 2. Plaisancian and Calabrian. 3. Post-Sicilian volcanic lavas, tuffs, etc., of the Volcano Laziale. 4. Zone of Red Dunes. 5. Travertines, late Pleistocene. 6. Fluviatile and eolian filling of lagoons, peats, etc. 7. Talus and alluvial cones.

Unlike the succession of the Lower Versilia, that of the Pontine Marshes is confined to a few metres above and below the present sea-level, yet in total it represents a much longer period, and the transgressive deposits of the Lower Versilia are here replaced by dune sands.

The earliest deposits are known from near Anzio, north-west of the Pontine Marshes (Fig. 60), where volcanic strata emanating from the Volcano Laziale interfere with the Pleistocene succession. Here, deposits of the Placentian and Calabrian (upper Pliocene) occur. A regression of the sea was succeeded by the Sicilian transgression. Deposits with a Sicilian fauna are found near Nettuno, not far from Anzio. Volcanic activities subsequently interfered and modified topography and hydrography of the district (formation of the Volcano Laziale). Volcanic tufas containing a Mediterranean flora separate the Sicilian from younger marine deposits with *Strombus bubonius*-fauna.

The post-*Strombus* sediments, corresponding to the succession of the Versilia, were well exposed along the Canale Mussolini at the north-western margin of the Pontine Marshes. The section observed at the "briglia II" (second weir) of the Canale Mussolini is the most complete (Fig. 61). It may be summarized as follows, beginning with the latest deposit.

—. Surface soil.

A. Reddish sands, predominantly eolian.

B. Yellow sands.

—Unconformity.—

C₁. Greyish-green sands with a well-defined horizon of calcareous crusts and concretions on top. The sands contain numerous concretions which often have broken the bones of fossils. *Elephas primigenius*, *Equus hydruntinus*. These sands are regarded as formed under cold and arid conditions.

C₂. Reddened sand, cross-bedded, with *Elephas primigenius* supposed to come from this deposit.

D. Grey sands, sometimes argillaceous, with plant remains. *Abies alba* abundant, indicating cool but humid conditions. *Elephas primigenius*.

—Unconformity.—

E. Lacustrine peaty sands. At the base vine-oak-hornbeam association, into which *Abies* and yew immigrate in the higher horizons, indicating a change from Mediterranean climate to a humid and temperate climate.

F. Beach sands with *Strombus bubonius*-fauna, sometimes loose, sometimes cemented. Reaching up to 10 m. above the present sea-level (Blanc, 1937*a*, p. 632). *Elephas primigenius* found. Climate warm. These sands rest on—

G. Volcanic tufas, which are perforated by *Lithodomus* and contain plants.

H. Marine Sicilian deposits.

If one attempts to correlate this section with others of the Mediterranean area, one can choose the *Strombus* deposits as the starting-point, since they do not occur above + 10 m. and therefore are probably of late Monastirian (late Last Interglacial) age. The peaty complex resting on the *Strombus* deposits and showing a gradual change from a Mediterranean to a cool and oceanic climate (E) is therefore likely to represent the beginning of the Last Glaciation. A. C. Blanc considers these deposits as older than the peats of

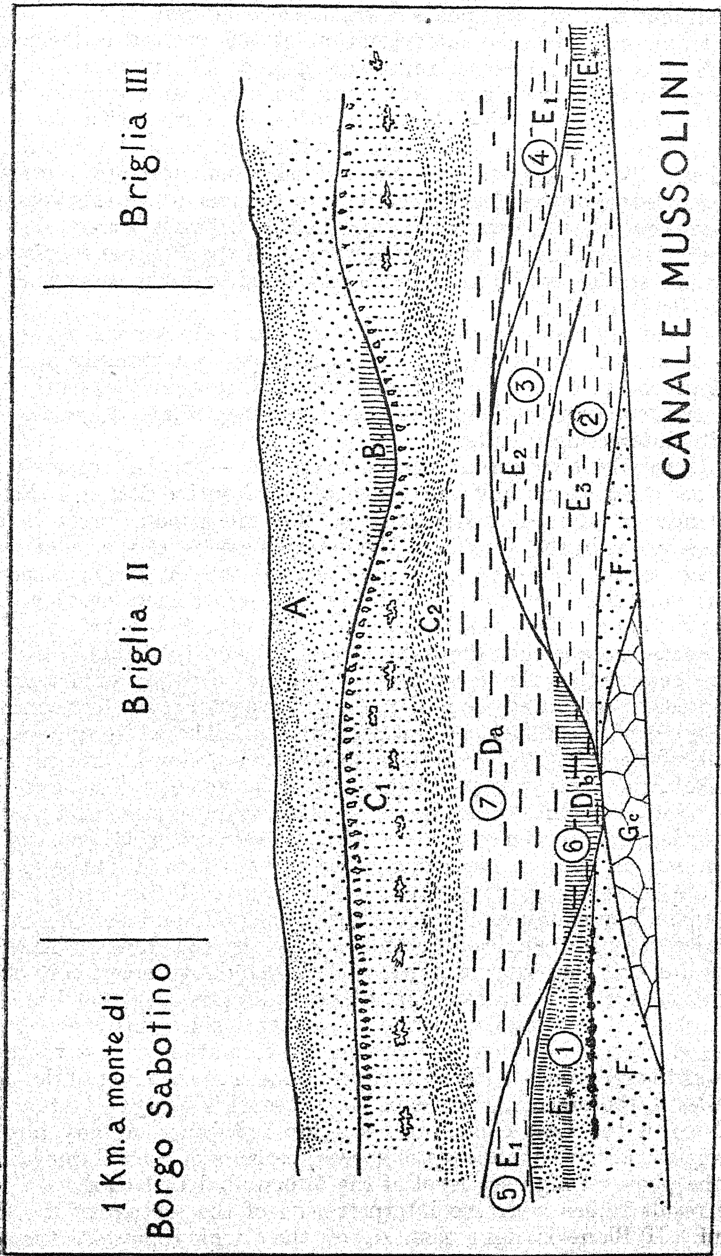


FIG. 61.—Section along the Canale Mussolini, Pontine Marshes, at Briglia II. For lettering, compare text, p. 110. After Tongiorgi (1937).

the Versilia succession, and as equivalents of the post-Monastirian regression which culminated in the first phase of the Last Glaciation.

Above (E), however, the interpretation of this section is less certain. There are two unconformities representing gaps of unknown duration. There is evidence of the climate changing from temperate-humid to cold-continental, but whether this change is to be correlated with the first or the second phase of the Last Glaciation, or with both, cannot be deduced from the section. Blanc suggests that the reddish sands (C_2) may correspond to the lower levels of the Versilia section, up to layer (C) of the Versilia, or the transgressive phase between LGl_1 and LGl_2. If this is correct, and there is corroborative evidence in the southern part of the Pontine Marshes, (C_1) of the Canale section would have to be correlated with the second phase of the Last Glaciation.

Yellow and red eolian sands (B and A) conclude the series. These fossil dune sands are the north-western end of a broad belt running parallel to the modern coast to join up with the Monte Circeo in the south, where their relative age can be delimited from the present-day end of the time-scale, with interesting results.

THE DUNE BELT OF THE PONTINE MARSHES.—The belt of fossil dune deposits occupied about half the width of the Pontine Marshes (Fig. 60). To the landward of it, marshes exist, so that the general arrangement is much the same as in the Versilia. The deposits consist of the reddish sands (A) and the yellow sands (B), both cross-bedded and the former exposed in numerous superficial sections, (A) being the weathering product of (B) according to Blanc. This weathering, apart from the Palæolithic finds made in these sands, proves that the dune belt of (A) and (B) is old.

To the seaward of the fossil dune belt a narrow strip of lagoons runs along the coast, separated from the sea by a very narrow, but continuous modern beach with a dune (the "white dune"). The white dune is, thus, the result of the activity of the sea at its present level. Its material is derived from the north-western part of the area, where erosion takes place.

The belt of the white dune, however, is not simply added on to the red dunes; the lagoon intervenes. This consists of several narrow lakes and strips of peat-marsh, all arranged in a line. The most important is the southernmost of the lakes, the Lago di Paola. It is a typical rias-lagoon (see Fig. 60), the main lake running parallel to the white dune and sending branches more or less at right angles into the area of the red dunes. That these branches are drowned river valleys is beyond doubt on account of their configuration and their continuation inland by streams. They were formed during a phase of low sea-level (at least $-$ 20 m., since this is the depth of the Lago di Paola) intervening between the formation of the white dune and that of the red dunes. Since the white dune is the product of the present high sea-level, the preceding phase of low sea-level is likely to be that of the third phase of the Last Glaciation, and the red dunes, at any rate their upper portion, would be made up of successive belts of coastal dunes formed during the phase of high sea-level of the interstadial LGl_2/LGl_3.

This result tallies with the interpretation of the section of the Canale Mussolini. If Blanc is right that C_1 of the Canale represents the second phase of the Last Glaciation, the dune sands covering this bed can very well be the product of the interstadial immediately following. On the

other hand, the red sands (C_2) would then be evidence of a similar period of dune formation in the interstadial LGl_1/LGl_2.

The uncertainty remaining in the sequence of the Pontine Marshes thus boils down to the lack of clear distinction between the supposed deposits of the first and second phases of the Last Glaciation in the Canale section. The fact that the approaches from the past (Last Interglacial) as from the present (modern sea-level and dune) lead to the same relative age of C_1 makes one confident that it does represent LGl_2, and inclined to neglect the unconformity between E and D as chronologically insignificant. E + D would then correspond to LGl_1 with a cool and humid climate, and C_1 to LGl_2 with a cold and continental climate.

The chief point to be settled is the climatic character of C_2, whether it is mild and interstadial, or more or less glacial. Analogy to the other dune deposits of the area pleads for the former view, the find of molars of the mammoth for the latter. These molars were, however, "not collected *in situ*, but their patination, and patches of red sand and calcareous concretions adhering to their surface, sufficiently indicate their derivation from layers C_2 and C_1" (Blanc, 1937*a*, p. 634).

PONTINE MARSHES: SUMMARY OF GEOLOGICAL SUCCESSION.—The evidence afforded by the Pontine Marshes thus suggests that—

(*a*) The Last Glaciation is divided into three phases, the first with a cool and humid climate, the second with a cold-continental climate, whilst for the third no climatic evidence is available in this area, but only a drop in sea-level.

(*b*) Three phases of dune formation correspond to three phases of high sea-level, the last being that of the present day, the other two those of the interstadials LGl_2/LGl_3 and LGl_1/LGl_2.

(*c*) The drop of the sea-level during LGl_3 amounted to at least 20 metres.

GROTTA ROMANELLI.—Turning now to the South of Italy, we meet with the Grotta Romanelli, near Castro in southern Apulia, which contains a most important series of late Monastirian and post-Monastirian deposits. This cave opens to the sea at about 10 m. above sea-level. It was discovered by P. E. Stasi in 1900, when he was studying the fossiliferous consolidated breccia which covers part of the entrance of this cave. In working out the results he collaborated with E. Regalia, and several notes were published (1904, 1905). A controversy ensued with regard to the age of the contained industries. Blanc settled this controversy by carefully excavating the deposits of the Grotta Romanelli, and by the publication of two extensive papers on the stratigraphy and the industry of this cave (1921, 1930). A short description of the Grotta Romanelli is also found in Vaufrey's book on the Italian Palæolithic (1928). G. A. Blanc's investigations supplied not only evidence of faunal changes, but also geological evidence of climatic oscillations in Apulia since the Last Interglacial. The cave, situated at only 40° N. lat., thus provides a landmark of the first order, which helps to extend southwards the chronology established for the upper Pleistocene of northern Europe.

The section (Fig. 62) is as follows (lettering as in G. A. Blanc, 1921, 1930), from the earliest to the latest:

(K) The deposits of the Grotta Romanelli rest on a somewhat irregular

rock floor at about 7·5 m. above low sea-level (G. A. Blanc); about 0·5 m. less if calculated from average sea-level. The rock-floor is covered with a beach-conglomerate consisting of coarse, rounded pebbles (level K). G. A. Blanc correlates this marine horizon with the *Strombus bubonius*-sea, in particular the latest and lowest of the known beaches. This is our

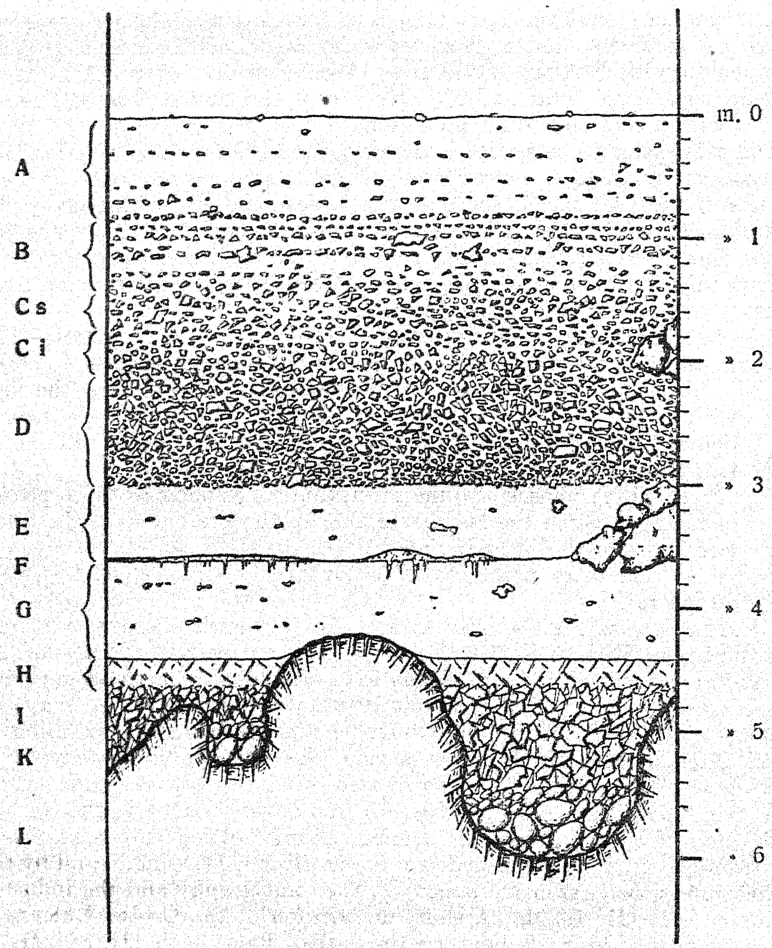


FIG. 62.—Schematic section of Grotta Romanelli, southern Apulia. After G. A. Blanc (1921).

Late Monastirian phase. Unfortunately, this bed is too coarse for shells to be preserved. On its surface was found a discontinuous layer of ash and charcoal which contained remains of *Hippopotamus*, *Dicerorhinus merckii*, an elephant (*? E. antiquus*), fallow-deer and rabbit, and of birds. This association of species indicates that the climate was still warm and of the Mediterranean type.

(I) The layer of ash and charcoal resting on the marine pebble stratum is covered by a deposit of angular rock-waste up to one metre in thickness. In places, this rock-waste (which must have come from the roof of the cave) shows traces of decalcification and transformation into argillaceous or loamy, whitish, yellowish or reddish-brown material. G. A. Blanc explains this decalcification as the result of chemical weathering under warm climatic conditions. Vaufrey, however, holds the view that this layer was formed under a climate with great thermal contrasts and that it testifies to the approach of the Last Glaciation (Vaufrey, 1928, p. 92).

The fauna of level (I) confirms the view of G. A. Blanc. It is a warm, Mediterranean fauna enriched by some extinct warm elements, and essentially the same as that of the underlying beach deposit. The following species have been found: Fallow-deer and rabbit very abundant, *Elephas, Dicerorhinus merckii, Hippopotamus, Bos primigenius*, horse, red (?) deer, roe deer, hedgehog, rock-pigeon (*Columba livia*), and other birds.

(H) The layer of angular debris is covered and sealed by a stalagmitic bed about 20 cm. thick. It shows that the climate had become more humid so that an ample supply of water rich in dissolved calcium-carbonate was available in the cave. The fauna of this bed is extremely poor, and most of the specimens were found in a hearth layer at its base. Apart from red (?) deer, rabbit and a goose (*Anser albifrons* Scop.), the hare (*Lepus europæus* Pall.) and the red fox are found, two species typical of temperate Europe to-day. Their presence so far south shows that the climatic conditions during the formation of the stalagmite (H) resembled those now observed north of the Alps. Since the overlying Terra Rossa deposit again contains a warm fauna, the stalagmite (H) represents the first, humid, oscillation of the Last Glaciation, with which we are already familiar from the Pontine Marshes and the Riviera caves.

(G) The lower stalagmite is covered by a red earthy deposit, called Terra Rossa (level G), which is about 0·8 m. thick. It is of a very deep, almost purplish red and consists of fine, though indistinct, strata of a sandy loam, interspersed with small angular pieces of limestone of local origin. The loamy matrix is, when dry, somewhat crumbly and loose.

It appears that most of the material of the Terra Rossa was derived from the normal Mediterranean weathering soil of the neighbourhood. There is, however, an admixture of sand present in this cave-deposit (Fig. 57). G. A. Blanc studied this sand and found it to be similar to desert-sand, many grains being rounded and having an opaque surface. On this sand G. A. Blanc based his view that the Terra Rossa (and the overlying Terra Bruna also) is eolian. Although mechanical analysis shows that the Terra Rossa of Romanelli is by no means a true loess, but a re-deposited weathering soil mixed with sand, the presence of this sand does provide evidence of wind-action and, therefore, of a certain dryness of the climate. The term "loess" is better not applied to the Terra Rossa (or the Terra Bruna) of the Grotta Romanelli.

The fauna of the Terra Rossa is composed of the following species:

Frequent: *Dicerorhinus merckii, Bos primigenius*, fallow deer, rabbit, *Otis tetrax, Columba livia*.

Rare: *Elephas antiquus, Hippopotamus*, red deer, roe deer, *Equus*

caballus, *Hyæna spelæa*, wolf, jackal (?), badger, *Lutra lutra*, *Microtus arvalis*, *Pelasgius monachus*, *Otis tarda*, and a fish (*Dentex vulgaris*).

The climate is well characterized by this fauna as warm and comparatively dry. This may be interpreted as either fairly dry all the year round or, more likely, seasonally dry, as at the present day. The presence of the rabbit and of the two species of bustards (grass-land birds) is noteworthy, also that of a species of wild dog which appears to be the jackal. On the other hand, the existence of woods is indicated by fallow deer and red deer, whilst *Hippopotamus* and otter testify to the neighbourhood of freshwater. The seal, *Pelasgius monachus*, shows that the sea cannot have been far. Not one element of this fauna suggests cool or cold conditions, either damp or dry. Blanc emphasizes that the fauna remains the same from the bottom to the top of the Terra Rossa, whose climatic character is best described as that of a warm forest-steppe such as it would presumably exist in Apulia now, had man not destroyed the natural plant-associations.

(F) Between the Terra Rossa and the overlying Terra Bruna a discontinuous layer of stalagmite is observed (F). It never attains more than 5 cm. in thickness, yet it represents a very distinct horizon since, where it is absent, the limit between Terra Rossa and Terra Bruna is equally sharp. G. A. Blanc stresses that the fauna of the Terra Rossa is homogeneous from bottom to top, and that the same applies to the Terra Bruna. The two faunas are totally different, so that there is no doubt that the stalagmitic level (F), whether actually present or merely indicated by the boundary between the two earthy deposits, is an important horizon corresponding to a period of considerable duration. The deposition of loose, apparently wind-blown, material had ceased, and the climate become sufficiently humid for stalagmite to be formed.

The layer (F) being so thin, faunal remains are practically absent. The only find so far made is part of a humerus of a *Capra*, identified by Blanc with ibex. This is an element which is absent from the Terra Rossa below, but found in the Terra Bruna above. It may be taken as an indication that the stalagmite (F) is more closely related to the Terra Bruna. Should the specimen prove to be ibex, one naturally would be inclined to interpret it as indicating a cool climate, especially in view of the southerly latitude of the locality. In any case two conclusions may safely be drawn, namely, (1) that during the formation of the upper stalagmite the climate was more humid than before and after, and (2) that this phase was less humid than that of the deposition of the lower stalagmite (H).

(E, D, C, B, A) The Terra Bruna, the uppermost deposit of the Romanelli section, is over 3·5 m. thick. G. A. Blanc subdivided it into a number of fairly distinct horizons (levels E to A).

In many respects the Terra Bruna resembles the Terra Rossa (Fig. 57). Both chiefly consist of a fine earth which is stratified by layers of fine sand and by layers of angular rock waste. The differences are found in the brown colour, the sandier grain of, and the abundance of coarse rock waste in, the Terra Bruna. Mechanical analysis shows that the Terra Bruna, too, is chiefly composed of a weathering loam mixed with wind-blown sand, and one cannot but accept Blanc's conclusion that the major portion of the Terra Bruna was blown into the cave by wind.

CLIMATE OF THE TERRA BRUNA PHASE.—The phase of the deposition of the Terra Bruna in the cave marks a pronounced change of climate. Wind-action was intense, and brown (not red) soil was exposed to the action of wind. At the same time, especially during the deposition of the midde portion of the Terra Bruna (levels C and D), thermoclastic destruction of the walls and the roof of the cave produced the rock-waste which is so abundant in the Terra Bruna. As the fauna suggests a cool climate rather than a warm one, this thermoclastic weathering is likely to have been caused by frost. No doubt the climate had changed from humid to decidedly continental, with a certain amount of frost and wind action.

The fauna bears out that the climate was cold, but by no means arctic. Among the large animals, the three frequent species are *Equus hydruntinus*, *Bos primigenius* and red deer. They characterize the assemblage (list in Blanc, 1921, pp. 13–15) extremely well. The wild ass is a form of open grass-lands, the urus requires water, and the red deer a certain amount of wood. Several biotopes thus appear to have been combined in the environment of the Grotta Romanelli at that time, namely, stretches of open country with grass and possibly bare spots (probably on the plateau above the cave), woods and shrubs in the natural cuttings of the cliff and on the then exposed marine erosion platform in front of it, and ponds and swamps on the same platforms. The sea cannot have been far, however, as *Monachus albiventer*, a seal, also is a member of this fauna. The remainder of the fauna fits into this setting. There are wild boar, badger, dormouse, lynx and wild cat preferring protection by woods, there is a large indifferent group, and there is the otter indicating the neighbourhood of water.

Among the birds there are not less than 14 species that are bound to water, besides two species of bustard which would have occurred in the grass-lands, an eagle and the griffon-vulture, two pigeons, the raven, the carrion crow (*s.l.*), jackdaw, and a thrush.

As regards the temperature required by this fauna, G. A. Blanc is strongly impressed by the occurrence of the hare and the fox, instead of the rabbit and jackal found in the Terra Rossa; of the ibex, of birds like the great auk, barnacle goose, and the lesser white-fronted goose, and others which are now restricted to more or less northerly regions. It cannot be denied that the aspect of the fauna is not Mediterranean but North European; yet it is not Arctic. In fact, every one of the species of the Terra Bruna has *occasionally* been found as far south as Malta, Egypt and Palestine (compare Despott, 1915; Ramsay, 1923). Their abundance in the Grotta Romanelli shows that conditions for them were then more favourable than now, but it is evident that such fauna would rapidly become established in Apulia if the climate changed from Mediterranean to, say, south Russian conditions. It is the latter type of climate, continental with cold winters and warm summers, with precipitation in spring and autumn, with steppe, wood-islands, and, in certain districts, water, that I incline to compare with the Romanelli climate during the formation of the Terra Bruna. The only two species which seem to support the claim of arctic conditions are the ibex and the great auk. The climatic value of ibex, however, is somewhat doubtful; it probably is a species adapted to mountainous scenery, and it is now on the verge of extinction after a period of very wide distribution. As regards the great auk (*Alca impennis* L.) (G. A. Blanc, 1928),

this now extinct species has also been found in Gibraltar (Bate, 1928) together with a fauna of a temperate character. In historical times it is said to have occurred as far south as the northern coast of Spain. Miss Bate (1928) summarizes the case as follows: "The occurrence of the Great Auk in the Mediterranean region in Palæolithic times does not necessarily imply a very different climate to that obtaining at the present day. That this bird was commonly known only from northerly latitudes within historic times may be responsible for its being usually considered an entirely northern, though not an arctic species." "It is generally considered that the final extinction of the Great Auk was largely due to man's interference, and it is possible that its retreat from the Mediterranean was also hastened by human agency."

The Terra Bruna reaches almost up to the roof of the cave. There are no petrological or palæontological changes throughout the deposit, and it is evident that its formation ceased because the cave was filled up. No later deposits, therefore, can be expected in the Grotta Romanelli.

Grotta Romanelli: Summary.—The climatic history of southern Apulia, as revealed by the sequence of strata in the Grotta Romanelli, is, thus, as follows:

(1) Sea-level about 8 m. above present average sea-level, warm conditions of the interglacial of the *Strombus* beach (Late Monastirian level).

(2) Recession of the sea begins. Conditions still warm and Mediterranean.

(3) The climate becomes oceanic.

(4) The climate changes to Mediterranean, drier and probably warmer than before.

(5) The climate becomes once more oceanic.

(6) The oceanic phase is followed by a cool and continental phase of climate.

It will be noticed that this succession is reminiscent of the successions established for middle Italy. The Late Monastirian high sea-level is succeeded by a humid oscillation, which is separated from a second humid oscillation by an interval of Mediterranean climate. The second humid oscillation, however, is followed immediately by a cool and continental phase. This is the same relation as established for the equivalents of the first and second phases of the Last Glaciation in the Versilia (p. 182) and, partly, the Pontine Marshes (p. 186). It is of the greatest importance that a humid LGl_1 and a LGl_2 which was first humid and then continental and cool are thus confirmed for *southern* Italy, on a latitude of approximately 40° N.

c. PALESTINE.

Mt. Carmel Caves: Section.—In the Near East it is Palestine that has provided us with sections sufficiently detailed to justify a climatic correlation with Europe. This is chiefly due to the excellent work done by Miss D. M. A. Bate and Dr. Dorothy Garrod.

Most attempts at correlating the pluvial phases observed in the Near East with the phases of the European glaciations have been contradictory and unconvincing. The reason is obvious: it lies in the assumption that the four main glaciations of Europe were undivided entities. Most

fortunately, the sequence established by Garrod and Bate (1937) for the caves of the Wadi-el-Mughara in Mt. Carmel in Palestine has produced unmistakable palæontological evidence for fluctuations of the climate. It is detailed enough to suggest a correlation with the phases of the Last Glaciation of temperate Europe.

The fauna of mammals of the two most important caves (Tabun and

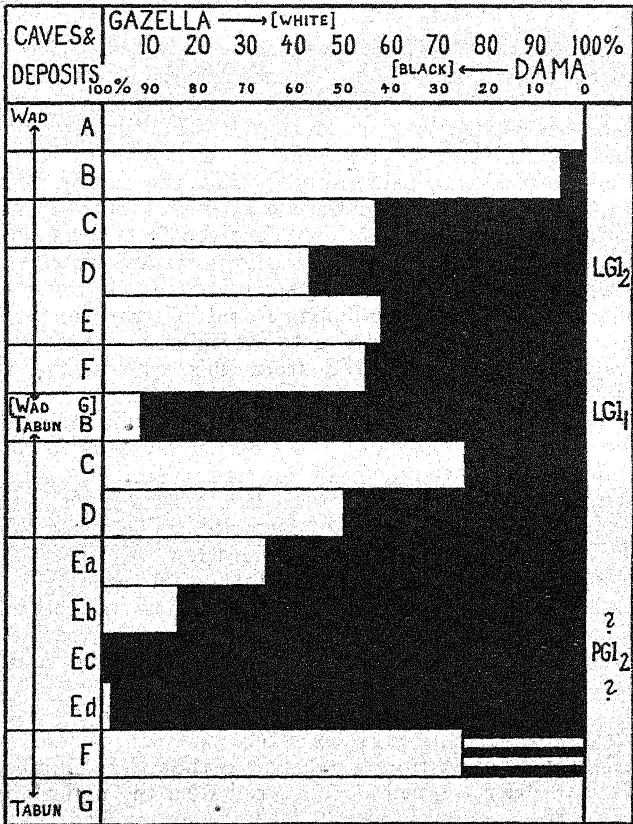


FIG. 63.—Relative frequency of Gazelle and Fallow Deer in the deposits of the Mt. Carmel caves, Palestine. Modified, after Bate, in Garrod and Bate (1937).

Wad) was analysed by Miss Bate (in Garrod and Bate, 1937) with the following results, beginning with the lowest level (Fig. 63) :

Tabun (G). This layer has yielded no vertebrate remains.

Tabun (F). The fauna consists of a bat with tropical relations (*Megaderma watwat* Bate), a shrew, a mole, several small rodents, *Dama mesopotamica*, gazelle, a frog or toad, and millipedes. It " consists entirely of distinct and primitive species, and includes an extinct genus." The fauna suggests a warm and damp climate.

Tabun (E). This level contains a rich fauna, including a number of

extinct species of early type. Some survivors from level (F) occur throughout. Halfway through the deposit, immigration of Asiatic forms increases, while the frequency of *Dama* decreases continually until equality with *Gazella* is reached at the top. "A warm, damp climate is indicated, perhaps tropical at the beginning, with gradual approach to drier conditions as level D is reached." This is clearly shown by the increase of *Gazella* (a steppe species) at the expense of *Dama* (a woodland species).

Tabun (D) and (C). "These levels have provided a rich fauna with several distinct forms of early type. Some species known in level (F) survive into level (D), which intergrades with level (E). Fresh immigration from Asia is suggested in level (D). The climate grows drier in level (C), but perennial water is present for the needs of Hippopotamus, etc." Gazelle increases considerably, whilst the fallow deer becomes rarer and attains a minimum of frequency in Tabun (C). At the same time, the primitive species which have survived from level (F) disappear, such as *Crocidura samaritana* and *Philostomys roachi*, which disappear in (D), and *Vulpes vinetorum*, *Ellobius pedorychus* and *Microtus machintoni*, which survive into (C) but are no longer found in higher levels. Numerous skeletons of a *Homo* with affinities to Neanderthal man (McCown and Keith, 1939) have been excavated from this level in the Tabun, and especially in the neighbouring Skhul cave.

Tabun (B) and Wad (G). With this level the fauna changes abruptly. None of the primitive mammals of the earlier levels is found. "From this level onwards the fauna is of modern type. Remains of *Dama mesopotamica* constitute the principal part of the collection, and this indicates a considerably increased rainfall." The relation *Dama* $\div$ *Gazella* is as high as about 91 $\div$ 9 (see Fig. 63).

This renders it probable that forests spread, and open grasslands became restricted, and also that the climate was on the whole much damper than at the present day. The average temperature, however, need not have been much lower than now; at least the fauna shows no signs of it.

Wad (F). The faunal assemblage of the level is of a "modern type, and includes new arrivals such as wolf, badger, marten, hare, etc." Gazelle is, however, once more frequent, so that the climate appears to have changed to drier conditions compared with the underlying horizon.

Wad (E). The same applies to this layer as to Wad (F). *Gazella* is even more frequent.

Wad (D). The fauna contains the same elements as Wad (F) and (E), but *Dama* becomes, for the last time, more frequent than *Gazella*.

Wad (C). The fauna remains essentially the same, but *Dama* becomes scarcer and *Gazella* more frequent.

Finally, in—

Wad (B) the fauna is of a modern type, though a few forms which are closely allied to Recent species but no longer found in Palestine still occur (for instance, *Erinaceus carmelitus*). Gazelle is now very frequent, and *Dama* decidedly rare. It is obvious that from Wad (C) onwards, the grasslands spread at the expense of the forest, and it is probable that the climate changed to a dry type.

Mt. Carmel Caves: Climatic Fluctuations and Correlation.—The fluctuations of the climate, more exactly the types of biotope prevailing at any particular time, are indicated by the relative frequency of gazelle and fallow deer as species representing grasslands and woodlands respectively. Miss Bate tabulated the two species; her results are reproduced in the diagram, Fig. 63.

At the time of formation of the earliest fossiliferous layer, Tabun (F), the fauna as a whole suggests a warm and damp climate, according to Miss Bate. The number of specimens of gazelle and fallow deer is too small for conclusions to be based on them (three gazelles, one fallow deer). While the next higher level (Tabun (E)) was forming, forest predominated. Towards the end of this phase, grasslands would have extended their domain; they attained to a maximum in the time of Tabun (D) and (C).

This dry phase is followed by a long period of damper, *i.e.* forest, conditions, with two maxima of forest during Tabun (B) (=Wad (G)) and Wad (D), separated by a drier phase (Wad (F), (E)). In Wad (C) times the climate again tended to become drier, and this process has continued through Wad (B), apparently with only minor oscillations, to the present day.

The most striking feature of this climatic succession is the presence of three maxima of forest, of decreasing intensity. In Palestine, the increase of forest signifies either a more even distribution of rainfall over the year, or a greater total amount of rainfall. Either case entitles one to call such phase a "pluvial" of some kind (for discussion of this point, see p. 205). The first of these three pluvials of our sequence is separated from the following two by a drier phase than that which separates the latter, and these appear to be more closely linked together.

Palæontological evidence supports this view, since Miss Bate found that a great faunal break occurred between Tabun (C) and Tabun (B) (+Wad (G)), coinciding with the beginning of the second pluvial phase of the sequence, after which the fauna assumed a modern aspect. This faunal break is highly significant from the chronological point of view. A similar break is observed in temperate Europe at the beginning of the first phase of the Last Glaciation, when a great many new forms appear for the first time and the specific composition of the fauna assumes a modern aspect, and also in many other parts of the world (Hopwood, 1936, 1940).

If one uses this palæontological evidence as a hinge for correlation, the first pluvial of the Mt. Carmel succession is likely to correspond to the (? second phase of the) Penultimate Glaciation, and the two later ones to the first and second phases of the Last Glaciation (Zeuner, 1938*b*, 1940). The third phase of the Last Glaciation would then appear to have left no traces in Palestine.

The "alternative hypothesis" of Vaufrey (1939), that the three maxima of *Dama* correspond to the three phases of the Last Glaciation, can be upheld only if the exceedingly pronounced character of the faunal break is disregarded. Fourteen species out of about 31 disappeared suddenly at the end of the first dry phase of the Mount Carmel sequence. Of these, Vaufrey selected one, *Hippopotamus*, in order to defend his hypothesis of the survival of this ancient-looking fauna into the Last Glaciation, and—strange to say—he added as a second *Rhinoceros merckii* which has not been found in the

Mount Carmel caves at all, and for the survival of which in the Near East no evidence is available.

One is inclined to correlate a sharp faunal break with the first climatic change after a long period of comparative stability, and not with a subsequent oscillation. Especially this is so when, as here, the "break" is almost purely one of extinction. The new forms, whose appearance completed the faunal change, appear only gradually; two in Tabun B (Wad G), one in Wad F, seven in Wad E, and one in Wad D.

Vaufrey offers no explanation of why wholesale extinction should have been postponed until the *second* phase of the Last Glaciation; nor is his contention convincing that this in fact happened in Italy. The truth is that we know almost nothing about the constitution of the Last Interglacial fauna of Peninsular Italy. We are therefore hardly in a position to assert that this fauna persisted until the second oscillation of the Last Glaciation.

The palæoclimatological significance of the Mt. Carmel caves lies in the evidence they provide for two pluvial phases corresponding to the Last Glaciation. Since the evidence is purely palæontological, it has not yet been possible to correlate them with the terrace deposits and other geological evidence from the Jordan Valley, to which attention has been paid by Picard (1932, 1937).

D. WESTERN MEDITERRANEAN AND SPAIN.

A few words have to be added concerning the Western Mediterranean. Work in this area has so far produced plenty of archæological evidence, chiefly owing to H. Obermaier's efforts, but the climatic succession of the Pleistocene would repay a closer study. What is known shows that the course of events in the Iberian Peninsula did not differ essentially from that established for Italy and Palestine.

GIBRALTAR.—The rock-shelter at Devils Tower in the north side of Gibraltar was discovered by Breuil and excavated by D. A. Garrod (1928). The mammals were determined by Miss Bate and the mollusca by P. Fischer. It is the only locality of the western Mediterranean area in which deposits with *Homo neanderthalensis* rest on a marine beach. The beach deposits reach up to 8·5 m. above the present sea-level, and the upper limit of the bore-holes of *Lithodomus* is found at 9–9·5 m.* These figures agree well with the altitude of the Late Monastirian sea-level in south France and Italy. Fischer found that the shells contained in the beach-deposits are chiefly Mediterranean, though a few Atlantic species occur also. They suggest a sea-temperature not very different from that of to-day, but the subspecific characters of some forms point to a warmer sea. "A specimen of *Ocinebra Edwardsi* recalls a modern variety which occurs in Madeira." "Several of the species found, notably *Trochocochlea articulata* and *T. turbinata*, are remarkable for their size. *Jagonia reticulata* also shows, but to a lesser degree, this increase in size. These observations support the correlation of the 9 m. level of Gibraltar with the lowest level of the *Strombus*-sea, the Late Monastirian of the Mediterranean shores.

The beds with human remains of the rock-shelter of Devils Tower

* J. Smith (1845) already described this ancient sea-level. According to him the *Lithodomus*-zone at the isthmus side of the rock is somewhat over 7 m. high and marked with clusters of fossil *Mytilus arcuatus* and barnacles.

contain a fauna of mammals (Bate, 1928) indicative of a mild climate with more woody vegetation than is now found in this part of the Iberian peninsula One is inclined, therefore, to regard it as more humid than the modern climate, but it is difficult to visualize, for comparison, the composition of the present-day fauna and flora of southern Spain previous to the interference of man.

The Spanish ibex is present. Again, the question arises whether fossil ibex indicates a colder climate or not. The geographical latitude of Gibraltar (36° N.) is lower than that of the Grotta Romanelli. The presence of ibex so far south and near the sea-level may be interpreted as proof for a colder climate, though it is by no means conclusive.

The avifauna, also studied by Miss Bate, comprises 33 species, all of which, except the great auk, still occur in Europe. The climatic interpretation of the great auk has been discussed (p. 195). It may, but need not, be evidence for a cooler clinate. Another interesting bird is the alpine chough (*Pyrrhocorax pyrrhocorax* (L.)), which was abundant at Devils Tower, occurring together with the red-billed chough (*Pyrrhocorax graculus* (L.)). These two species are now restricted to different altitudes, the alpine chough being found in high mountains only. Their simultaneous occurrence at Gibraltar suggests that the climate was suitable for both species, namely one characterized by cooler summers. Both species have been recorded also from the upper layers of the Grotte de l'Observatoire and from the Grimaldi caves (Boule, 1927).

Thus, the fauna of the Mousterian beds above the fossil beach of Gibraltar seems to indicate a climate somewhat damper and cooler than the present. The three items on which this view is based (frequency of ibex, great auk, alpine chough) are, taken singly, not conclusive, but the simultaneous occurrence of the three species lends support to the view that these beds were deposited during the incipient stage of the Last Glaciation, after the sea-level had begun to recede from the Late Monastirian level. The Neanderthal skull from Gibraltar is, on this view, contemporary with that from the Monte Circeo in Italy (A. C. Blanc, 1939*a*; Zeuner, 1945).

CASTILLO CAVE, NORTHERN SPAIN.—The fluctuations of the climate in northern Spain are best illustrated by the Castillo Cave, near Villacariedo in the province of Santander. As shown by the work of Obermaier (1924, pp. 161–166) and A. C. Blanc (1937*d*, p. 11), there is evidence for repeated changes of climate. In the following summary of the section, the unfossiliferous clays which separate the fossiliferous horizons are omitted. The accumulation of bones in the latter is entirely due to early man. Several stalagmitic phases mark periods when the cave became too damp for human occupation. Generally speaking, the fauna suggests forest (red deer), with the exception of an episode of steppe characterized by the abundance of horse.

Layers (x) to (z). Late Postglacial.

(w) Occupation layer.

(v) Stalagmite. Damp phase. ? LGl_3.

(u) Chiefly red deer. *Cyprina islandica*. No reindeer. Climate milder than in (s).

(s) Chiefly red deer, but some reindeer. Cold, but forest reappearing.

(O) to (Q). Chiefly horse. Reindeer present. *Cyprina islandica*, a marine bivalve no longer found off the north coast of Spain. Cold steppe. ? LGl_2.
(K) to (M). Chiefly horse. Steppe, but no evidence of cold. ? Oncoming LGl_2.
(H) Chiefly red deer. *Dicerorhinus merckii.* Forest climate.
(G) Stalagmite. Damp phase. ? LGl_1.
(D) to (F). Chiefly red deer. *Dicerorhinus merckii. Elephas antiquus* in (F). Forest climate. No cold forms.
(C) Stalagmite. Damp phase.
(B) Chiefly red deer. *Dicerorhinus merckii.* Forest climate.
(A) Chiefly cave bear. Rare: reindeer and marmot.

This succession indicates a threefold division of the Last Glaciation into a first damp phase (G), a second dry and cold phase (O)–(Q), and a third damp phase (V). Horizons (D) to (F) are suggestive of the Last Interglacial, with *E. antiquus.* If this is correct, (C) and (A) would correspond in part to the Penultimate Glaciation.

OLHA, FRENCH PYRENEES.—This succession may be compared with that at Olha, on the French side of the western Pyrenees, where deposits correlated with (G) of Castillo are definitely cold in character, containing reindeer, woolly rhinoceros and mammoth (Obermaier, 1924, 1935, 1937*a*; A. C. Blanc, 1937*d*). On the French side of the Pyrenees therefore a cold climate might have prevailed in LGl_1, while conditions on the Spanish side were those of a pluvial.

Judging by the evidence at present available, the upper Pleistocene of the Iberian Peninsula thus appears to corroborate the climatic sequence established for the Mediterranean region.

E. THE ASTRONOMICAL THEORY APPLIED TO THE MEDITERRANEAN REGION.

SUMMARY OF PALÆOCLIMATIC EVIDENCE.—The preceding parts of this chapter were wholly concerned with the relative chronology of the Mediterranean upper Pleistocene, chiefly in its climatological aspects. The results may now be grouped (Fig. 64) according to the geographical latitude of the localities. This table may serve as a basis for an attempt at establishing an absolute chronology with the aid of the radiation curves.

Before we embark upon the theory of the climatic fluctuations in the Mediterranean area, it will be useful to recollect the main points derived from the evidence afforded by the sections:

(1) During the Last Interglacial (Monastirian beaches) the sea was warmer than at the present day.

(2) The most complete sections confirm that, as in temperate Europe, there were three phases of the Last Glaciation.

(3) Of these, the third was the weakest, and the second the most intense.

(4) Climatic evidence for LGl_3 has been found only to the north of 43° N. lat.

(5) LGl_2, on 40° N. and north of it, can be subdivided into a first, humid, subphase, and a subsequent cold and mostly dry, more continental, subphase. On 33° N. lat., however, this phase appears to have been humid throughout.

(6) LGl_1 is represented by a humid phase everywhere; it was cool N. of 42° N., and temperate S. of it.

(7) It follows from (4), (5) and (6) that there were latitudinal differences of the climate which are most pronounced with regard to LGl_3 and least pronounced with regard to LGl_1.

(8) It follows from (5), in connection with (4) and (6), that the ordinary type of climatic phase representing the glacial phases in the Mediterranean is a phase of humid, or oceanic, character, which in the most intense conditions (LGl_2 north of 40° N.) was followed by a cold and continental sub-phase.

INTERFERENCE OF RADIATION CLIMATE AND SECONDARY EFFECTS OF GLACIATION.—The fluctuations of the radiation received by various latitudinal zones of the earth, which have explained in a comparatively simple

LAT.	44°N.	44°N.	43°N.	42°N.	40°N.	36°N.	33°N.
	RIVIERA	VERSILIA	CASTILLO	PONTINE MARSHES	ROMANELLI	GIBRALTAR	MOUNT CARMEL
POST-GLACIAL							DRY [STEPPE]
LGl_3	HUMID (WEAK)	COOL-HUMID	HUMID	SEA-LEVEL LOW			
$LGl_{2/3}$		MEDITERRANEAN	[FOREST]				
LGl_2	COLD FOREST / HUMID	COLD-CONTINENTAL / COOL-HUMID	COLD-CONTINENTAL [STEPPE]	COLD-CONTINENTAL	COOL-CONTINENTAL / HUMID		HUMID [FOREST]
$LGl_{1/2}$	COOL (ABOVE?) -TEMPERATE	MEDITERRANEAN	[FOREST]		MEDITERRANEAN		DRY [STEPPE]
LGl_1	HUMID	SEA-LEVEL AT -90 M.	HUMID	COOL-HUMID	HUMID	TEMPERATE FOREST	HUMID [FOREST]
$LIgl$	SEA WARMER THAN NOW		[FOREST]	SEA WARMER THAN NOW	WARM 8M.-SEA-LEVEL	SEA WARMER THAN NOW	DRY [STEPPE]
PGl_2	HUMID		HUMID				HUMID [FOREST]
$PGl_{1/2}$	TEMPERATE						
PGl_1	HUMID						
	TEMPERATE						

FIG. 64.—Table of the climatic phases of the later Pleistocene in the Mediterranean area.

manner the repeated alternations of advance and retreat of the Scandinavian and Alpine ice-sheets, must have influenced the Mediterranean climate also, though in a different way.

Furthermore, it has been expounded by many climatologists that the ice-caps of northern and central Europe compelled a large number of barometric depressions to take the path along the Mediterranean instead of moving across central Europe which, while the ice-caps lasted, was more liable to be covered by cold and heavy anticyclones than is the case at present. The cold and relatively dry wind which emanated from the ice- and snow-covered areas of Europe must have influenced the Mediterranean climate also, especially further east. But these distant effects of the ice-anticyclones did not develop before the ice-caps had attained considerable proportions. *They were retarded relative to the direct effects of the changes in the radiation* as much as were the maxima of extension of the ice relative to the radiation phases causing them in north and central Europe. It is

apparent that, in the Mediterranean, these conditions resulted in a complicated interference, or overlap, of pure radiation climate and secondary "distant" effects of the glacial climate.

To-day no more than an estimate can be made of the probable effects of these factors. In doing so, however, one realizes that what can be deduced theoretically in this manner agrees astonishingly well with the observed facts as tabulated in Fig. 64.

Radiation Curves for the Mediterranean.—If one takes the present-day climate as the starting-point and considers the fluctuations of solar radiation during the Pleistocene for the latitudes of 45° and 35° N., one is struck by the general resemblance of these curves (Fig. 52) with those of the higher latitudes. Three minima of summer radiation, corresponding to the three phases of the Last Glaciation, occurred at approximately the same times in the Mediterranean as they did in the north.

Relative Intensity of Minima.—The relative intensity of these minima, however, is different. Whilst on 75° N. lat., R.M. 25 was somewhat more intense than R.M. 115, on 35° N. lat., the former (here R.M. 22) was a very weak minimum as shown by the following figures :

Summer minima in canonic units.	LGl_1.		LGl_2.		LGl_3.	
	Can. un.	Years.	Can. un.	Years.	Cal. un.	Years.
75° N. lat.	−639	(115,000)	−581	(71,900)	−646	(25,000)
35° N. lat.	−454	(116,100)	−317	(71,900)	−166	(22,100)

As usual, the corresponding winter half-years have similar, but positive values, indicating surpluses of radiation. From these figures it is apparent that the direct climatic effects of R.M. 22 must have been much less noticeable in the Mediterranean than that of R.M. 25 in northern Europe. The fact that geological evidence for R.M. 22 has come forward north of 43° N., but not south of this latitude, strongly corroborates this theoretical conclusion.

Climatic Effects of an Intense Minimum of Summer Radiation.—In order to deduce the direct and indirect effects of one of the intense minima of summer radiation on the Mediterranean climate, the effects in the north of Europe may briefly be summarized.

In northern Europe, the most important consequences of a radiation minimum in summer coupled with a maximum in winter were twofold :

(*a*) A great increase of atmospheric activity in winter, with plenty of precipitation falling as snow in the higher mountains, and—

(*b*) A decrease of warmth in summer, whereby the preservation of snow-sheets is favoured. Thus, an increase in size resulted of the snow-fields which were able to persist through the summer, since only a portion of the annual amount of snow thawed, the remnants accumulating and gradually forming permanent snow-caps and ice-caps. In this manner, a glaciation was initiated. Its maximum was reached much later, probably at a time long after the summer minimum of radiation, which lasted only for a few thousand years.

From this it is evident that at the time of a summer minimum of radiation the secondary effects, like the anticyclonic conditions in north and central Europe, and the passage of a larger number of depressions through the Mediterranean, were not yet in evidence. Whilst in Scandinavia snow was accumulating to form an ice-cap, central Europe and temperate western

Europe had a pronouncedly oceanic climate with cool summers and very mild winters. In the Mediterranean also, summer radiation was less and winter radiation more than at the present day.

In what way was, then, the Mediterranean climate modified, compared with to-day? In agreement with Simpson's views I consider it probable that winters with increased radiation resulted in an increase of precipitation. The summers with reduced radiation may have been comparatively clear, and inevitably cooler than at present. Though the annual average of precipitation need not have been larger than nowadays, such a climatic phase would have favoured the spreading of a temperate (central European) flora and fauna in the Mediterranean area. In the fossil state, such flora and fauna will cause the impression that it lived in a true "pluvial" phase with a comparatively low temperature. Yet the annual mean of temperature was perhaps not lower than at the present day. This type of climatic phase may be called a *pseudopluvial*; it marks a period of low summer radiation in the Mediterranean.

While the ice-caps in the north grew in size, the secondary effects of the glaciation began to make themselves felt. The best-known of these effects is the diversion of many depressions to the southerly path along the Mediterranean. These depressions must have brought to the Mediterranean an actual increase of the annual mean rainfall, so that one is justified in saying that, provided the glacial phase under consideration was sufficiently intense, the pseudopluvial was followed by a real *pluvial*.

Another secondary effect was that, presumably, the gradient of atmospheric pressure from north Europe to the Mediterranean was at times far greater than at present. Large portions of north Europe were covered with ice, and wide areas with snow, for many months. It is likely, therefore, that the conditions which nowadays prevail in winter, with high pressure over the snow-covered east of Europe and lower pressure over the Mediterranean (see Köppen, 1931, pl. 5), extended further west during the glacial phases, were more intense and lasted through the major part of the year. This would have caused comparatively frequent inrushes of cold air into the Mediterranean.

The Mediterranean climate during the maximum of a glaciation thus appears to have been colder and damper than to-day, and this under unsettled atmospheric conditions with frequent and sudden breaks of the weather. This type of climate would have favoured the formation of ice- and snow-fields on the high mountains of the Mediterranean.

Meanwhile, however, the radiation was returning from the type that produced the pseudopluvial to more or less the average as it obtains to-day. Summer radiation increased and winter radiation decreased—a change which might easily have produced a continental tendency in the pluvial climate of the Mediterranean, a tendency which would have been most pronounced towards the end of the pluvial. Fauna and flora must have been capable of enduring this type of climate, in fact, mammoth and woolly rhinoceros have been found in Italian deposits, and Tongiorgi found that the mountain pine and the Scotch pine grew at sea-level in the Versilia during the second phase of the Last Glaciation.

When the ice-cap over northern Europe began to melt down under the influence of warmer summers, the glacial anticyclone was weakened corre-

spondingly, and the distant effects disappeared. It is known that this process was more rapid than the growth of the ice-sheet. The Mediterranean pluvial climate must have deteriorated with equal rapidity and the modern type of Mediterranean climate taken its place.

SUMMARY OF THE SUBPHASES OF A COMPLETE MEDITERRANEAN PLUVIAL.—Summarizing our theoretical deductions, three subphases of the complete pluvial cycle of the Mediterranean type can be distinguished :

(A) Subphase of decreased summer radiation and increased winter radiation. Summer cooler than to-day. Precipitation less restricted to spring and autumn than to-day. Therefore, spreading of central European forest into Mediterranean. Annual total of precipitation not necessarily greater than to-day. During this period ice-caps growing in the north of Europe. "Pseudopluvial."

(B) Period of greatest extension of ice-sheets in northern Europe. Many depressions diverted from the central European path. Some cause heavy orographic and warm-front snow-falls over Scandinavia, others move across the Mediterranean. Summer radiation increasing, winter radiation decreasing, unsettled weather in summer with much rain and rapid and intense changes of temperature. Winters cold ; with frost in the northern Mediterranean. "Pluvial" in the Mediterranean area, with pseudo-continental climate north of approximately 40° N. lat.

(C) Period of the disintegration of the glacial anticyclone. Total of precipitation in Mediterranean decreasing. Rapid return to the present-day type of Mediterranean climate.

WEAKER PHASES.—Less intense glacial phases will not have been able to influence with their distant effects the climate of the Mediterranean as strongly as did the major glacial phases. Subphase (B), in particular, will have been weaker generally, and frosty winters will have been rare. A mild pluvial was the result.

SOUTH SHORE OF MEDITERRANEAN.—In the countries bordering the Mediterranean on the south side, the distant effects were naturally weaker than in the north, and mild rainy pluvials the rule, since during subphase (B) only the rain-bringing depressions, but not the effects of cold emanating from the glacial anticyclone, would have reached this zone.

COMPARISON OF THEORY WITH OBSERVATION.—It is not too much to say that the conclusions arrived at in the preceding paragraphs agree in every respect with the evidence available at present. The second phase of the Last Glaciation, for instance, illustrates well the succession of the mild-humid pseudopluvial by the true pluvial with frost-winters north of 40° lat. on the Italo-French Riviera, in the Versilia, and the Grotta Romanelli. The third phase of the Last Glaciation which, according to the radiation curve, would have been weak and inconspicuous in the Mediterranean, has apparently left traces only on 43° N. and north of it. The first phase of the Last Glaciation was more intense than the third, and in many places pronouncedly humid, but evidence for the cold-continental second part of the pluvial is not satisfactory. Whether this means that this phase was less cold than LGl_2, or damper, cannot be decided, but it is most remarkable that in temperate Europe also the first phase of the Last Glaciation differs from the second by its less pronouncedly arctic character in spite of an even larger extension of the ice-sheet.

The fact that one encounters a corresponding difference in the Mediterranean area supports the correlation with the glacial phases as expounded here. We are justified, therefore, in applying the dates provided by the radiation curve to the pluvials of the Mediterranean area, keeping in mind that the summer minimum of radiation was contemporaneous with the "pseudopluvial" subphase in each case. Taking the figures for 35° N. as an average, we can thus say that the three pluvial phases corresponding to the Last Glaciation occurred at about 116,000, 72,000 and 22,000 years B.P.

In concluding this preliminary survey of the Mediterranean it must be stressed once more that, although the evidence at present available is strongly suggestive of the correlation put forward in these paragraphs, it is scanty compared with the abundant evidence available for the chronology of temperate Europe. Much more work is needed in the Mediterranean area to confirm or to modify this preliminary chronology, and also to extend it further back into the past.

CHAPTER VIII

THE ASTRONOMICAL THEORY APPLIED TO THE TROPICAL ZONE OF AFRICA, TO SOUTH AFRICA AND TO ANTARCTICA

A. EXTENSION OF THE ABSOLUTE CHRONOLOGY OF THE PLEISTOCENE TO THE TROPICAL ZONE.

SINCE the chances of a correlation of the climatic oscillations with the fluctuations of solar radiation are fairly good in the Mediterranean area, one might feel inclined to extend such correlation to the tropical zone with its pluvial phases, especially in view of the palæoclimatic setting given by some recent authors to certain archæological discoveries in tropical East Africa.

The prospects of doing so, however, are very slight for the time being, since our knowledge, both as regards the geological evidence and the theoretical climatic interpretation of the radiation curves, is not advanced enough. Moreover, a study of the possibilities of such an approach shows clearly that the suggested correlation of certain tropical pluvials with certain glaciations of Europe is not only unfounded, but in some cases definitely wrong. It was chiefly based on the mistaken, though most widely accepted, assumption of the strict contemporaneity of tropical glaciations and pluvials with European glaciations. This is a typical example of uncritical acceptance of an assumption born from the desire of simplifying, which is so current in scientific thought, though it often violates the facts. The following paragraphs, therefore, intend to demonstrate the difficulties of correlation between the temperate and the tropical regions, and at the same time to show a possible way of attacking the problem. To state briefly my view in advance, as regards the geological aspect of Pleistocene chronology in the tropics, a general correlation has still to rely on palæontological evidence and not on the correlation of suspected or true pluvials, and the definite link-up with Europe can only be achieved in the future by following the river terraces down to sea-level, and by using the ubiquity of certain high sea-levels of the Pleistocene as a relative time-scale (see Chapter IX, p. 252).

The links between the Pleistocene of the Mediterranean area and the tropical zone of East Africa are few. Apart from the terraces of the Nile which cannot be discussed in this context and the climatic character of which is by no means clear, there are the Kharga Oasis, south-west Arabia, and Abyssinia, providing stepping-stones to Kenya and Tanganyika. The Fayum with its lake will, in future, provide another important link, but too many points of its Pleistocene succession are still a matter of controversy (Thompson, Gardner and Huzayyin, 1937).

KHARGA OASIS.—Kharga Oasis is situated in the Egyptian desert, on $25\frac{1}{2}°$ N. lat. Gardner (1932, 1935) and Caton-Thompson (1932; also joint paper, 1932) studied the deposits of freshwater tufa around extinct springs of this oasis and their connection with phases of erosion and aggradation. Miss Gardner established the following succession (1932, p. 403; Caton-Thompson and Gardner, 1932, p. 390; Caton-Thompson, 1932, p. 130; Gardner, 1935, p. 517), beginning with the earliest identifiable event:

(1) Deposition of tufa on plateaus, previous to the cutting of the wadis: some rain.

(2) Great erosion, valleys cut: increased rainfall.

(3) Filling of these early valleys by coarse breccia, on large scale for a long period: little or no rain.

(4) Re-establishment of more favourable conditions, trees and ferns growing on plateau and scarp, tufa, gravel and silt deposited on the breccia: some rain.

(5) Intense erosion, accompanied by formation of a gravel sheet; maximum of moist conditions.

(6) Aggradation of silt and gravel, due to decrease in precipitation, followed by tufa formation: less rain.

(7) Erosion of earlier deposits, main topographical features established: more rain, second maximum on the rainfall curve.

(8) Aggradation of silt and gravel, followed by tufa: less rain.

(9) Erosion on much smaller scale than before, followed by formation of 7 m. gravel terrace: slight humid oscillation followed by a drier phase, final conditions drier than in (8).

(10) Erosion on still smaller scale, followed by formation of 5 m. gravel terrace: very slight humid oscillation, followed by dry conditions leading up to those of the present day.

This climatic sequence admits of an interesting interpretation in the light of the radiation curves. This interpretation is put forward here not as a final solution for the chronology of Kharga Oasis, but as an illustration of the fact that the astronomical theory of the Pleistocene is not inconsistent with the geological evidence found as far south as 25° N. lat.

Whilst it is difficult to assess the relative intensities of the earliest damp phase, Miss Gardner has obtained a remarkable result concerning the last four. They were successively less intense (phases 5, 7, 9, 10). Now, these damp phases were preceded by a period of deposition of breccia, which might well represent a prolonged period of dry conditions resembling those of the present-day and, therefore, the Last Interglacial. This suggestion of a rough chronological placing of the later Kharga deposits would imply that there were four damp phases since the Last Interglacial, each weaker than its predecessor, and the last being decidedly very weak.

It is interesting to note that the radiation curve for 25° N. (Fig. 52) shows, in fact, four summer minima of decreasing intensity at 116,000, 94,000, 72,000 and 22,000 years B.P., the minimum of 94,000 being one that is inconspicuous further north, but which becomes the most intense of all four as one approaches the equator. It is tentatively suggested, therefore, that in the desert zone at 25° N., the climatic effects of the changes of solar radiation were not radically different from those on the southern shore of the Mediterranean, in so far as summer minima coupled with winter maxima

of radiation produced an increase of rainfall. It is further conceivable that phases (5), (9) and (10) of Kharga are the three pluvial phases which represent the three phases of the Last Glaciation in Europe. The existence of a weak terrace corresponding to LGl_3, evidence for which is absent from the southern part of the Mediterranean, is easily understood if one considers the great differences produced in the desert climate by even a very moderate amount of rainfall.

SOUTH-WEST ARABIA.—In South-West Arabia, about 15° north of the equator, a sequence of wetter and drier phases has been recognized. Only two expeditions have paid attention to the problem of fluctuations of the Pleistocene climate, that of the Egyptian University to Yemen (Huzayyin, 1937) and the Lord Wakefield Expedition to the Hadhramaut (Caton-Thompson and Gardner, 1938, 1939). The evidence available points to a Pleistocene climate marked by two major pluvials of which the earlier was more intense, each of which may be subdivisible into at least two subphases.

It must be kept in mind that the climate of south-west Arabia is at present comparatively dry because of its position near the northern edge of the monsoon belt. The possibility, therefore, that the pluvial phases of south-west Arabia were caused by a shifting of the monsoon zone has to be considered. The repeated displacement of the caloric equator as calculated by Milankovitch (1938*a*, *b*) alone renders this type of climatic change probable. On the other hand, the oscillations of solar radiation, and particularly their distribution over the seasons, are likely to have influenced the Pleistocene climate of this area. The amplitudes of the fluctuations were often much higher than in the northerly latitudes. Thus, there are several theoretical reasons for the occurrence of wet phases in southern Arabia during the Pleistocene, but it is impossible at present to disentangle them, especially since the geological evidence needs further substantiation.

TROPICAL AFRICA.—Crossing the Red Sea to Abyssinia, we enter the zone of the tropical climate, where a definite rainy season occurs once or twice annually. Abyssinia, whose climate is much modified by the mountainous nature of the country, lies in the northern belt with a single rainy season during the summer of the northern hemisphere.* As one goes south the rainy season extends over a larger part of the year, but the maximum of the rains still occurs in north-summer.

Between about 5° N. and 5° S. lat.,rain falls at all seasons, but there are two distinct maxima, in March–April, and in November–December. This is the equatorial zone proper, in which one finds the tropical rain forest most typically developed. In East Africa, the climate of this zone is again modified by altitude and other factors, and much drier than one would expect, but the distribution of the rains is not obscured (see Köppen, 1931, fig. 21). Kenya, Uganda and Tanganyika belong to this zone. South of this equatorial zone a reversal takes place, there being one single maximum of rainfall, in south-summer (December to April), and a more or less pronounced dry season from July to October.

It is necessary to visualize that the climates of this part of the world vary much more with the latitude than for instance in Europe. The difference of the climates of, for instance, southern England and southern Norway

* One of the complications of the Abyssinian climate is the presence of two maxima of rain, as observed in the equatorial zone, as far north as 9–10° N. lat.

is negligible compared with that of, for instance, the northern frontier of Uganda and Khartoum, where the rainfall dwindles to a tenth of the amount observed in Uganda. Similarly, local differences due to topographical features can be very great.

For this reason it is exceedingly difficult to interpret climatic fluctuations established, or suggested, for any of the tropical zones. It is equally risky to correlate over distances of several hundred kilometres. Before elaborating this point, some instances of the kind of evidence produced for oscillations of the Pleistocene climate in tropical Africa may be given. They are of two kinds, namely, (*a*) lake terraces indicating changes in the size of bodies of standing water; (*b*) fluviatile and eolian deposits and soils indicating changes in the amount of run-off and of moisture available on the land-surface.

Abyssinia.—Abyssinia is the latest of the East African countries to be explored. Nilsson (1940; review of his work by Kent, 1942) found that the basin of the lakes called Zwai and Shala exhibits an ancient beach 150 m. higher than the present water level, cut into older Pleistocene deposits and believed to be of upper Pleistocene age. There are numerous intermediate

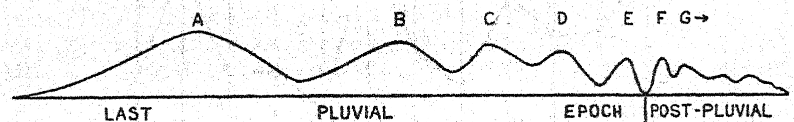


Fig. 65.—Variations in the levels of the lakes in the Nakuru Basin, Kenya, during the Last Pluvial epoch, as determined by Nilsson. After Nilsson (1940), modified.

beach-lines between the highest and the modern level, to which we shall refer again later on.

Similarly, Lake Tana, which is considered to have been dammed up by lava flows during the last interpluvial, exhibits a succession of beach lines.

Kenya.—In Kenya, as in neighbouring Uganda, important work has been done. Both countries are within the equatorial zone with double rainfall maximum, but on the whole their present climate tends to be drier than one would expect it to be on theoretical grounds.

Nilsson (1940) studied in detail the deposits and beaches of Lakes Nakuru and Naivasha, situated in the Kenya branch of the Rift immediately south of the equator. These lakes formed one great lake at certain periods. The beaches are arranged in a sequence of descending levels which, according to Nilsson, are all of upper Pleistocene age and represent the oscillations of the climate during and after the last pluvial (Fig. 65).

Nilsson undertook to correlate the stages of the Nakuru-Naivasha basin of Kenya with those of the Zwai-Shala basin and of Lake Tana in Abyssinia (and also with the Fayum). In doing so, he used the differences between the heights of successive lake-levels. Represented in the form of a graph (Fig. 66), they show a reasonably good agreement, especially between Lake Nakuru and the Zwai-Shala basin. At first sight this agreement suggests a common climatic cause for these consecutively lower lake-levels in East Africa, and it is thus interpreted by Nilsson, but the difficulty of establishing the intervening low lake-levels for all the areas compared leaves a

serious uncertainty to be overcome. In any case, however, a way towards establishing a chronology founded on geology irrespective of archæological considerations is opened here.

Nilsson's earlier work further provided the basis for the climatic sequence which Leakey (1931, 1936) uses in connection with his archæological work. It is based in part on lake levels, in part on cave deposits, all situated in the Nakuru-Naivasha basin, and distinguishes three pluvials, each with two maxima, followed by two after-phases (Fig. 69).

UGANDA.—In Uganda, Wayland's valuable work has resulted in a

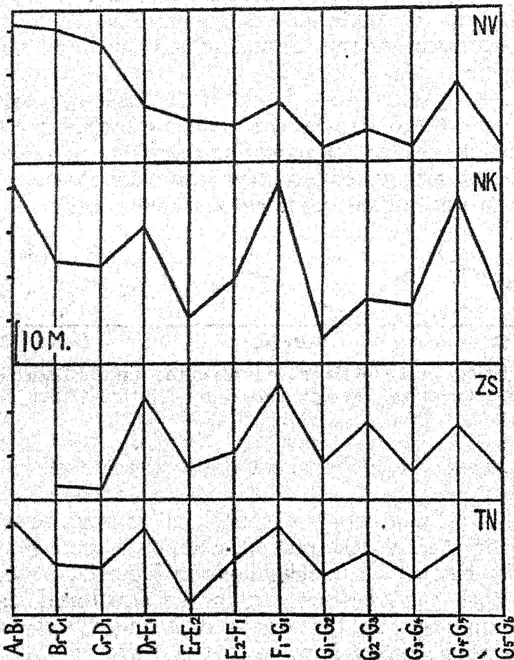


FIG. 66.—Diagrams of the height-differences between successive lake-levels in the basins of Naivasha (NV) and Nakuru (NK) in Kenya, Zwai and Shala (ZS) in Abyssinia, and Lake Tana in Abyssinia. Vertical scale, 10 metres. After Nilsson (1940), modified.

climatic sequence which recognizes two major pluvials, each with two sub-phases, and separated by a major dry phase or interpluvial, and followed by two moist after-phases (1934). This is, in fact, much the same sequence as that of Kenya, since Wayland's second pluvial combines the Kamasian and Gamblian pluvials of Leakey. Wayland regards the question of two or three pluvials largely as one of definition: "Available evidence points to two main pluvials, the second of which (and perhaps the first) was a double one or, according to how one defines a pluvial period, three pluvials and two subsequent epipluvials" (Wayland, 1939, p. 145). This sentence sums up in a cautious manner the results so far obtained in Kenya and Uganda.

It shows that some of the duplications of the pluvial phases (as accepted by Leakey) are still disputable. It further emphasizes, by giving preference to the system of two (instead of three) major pluvials, the position of the major interpluvial, into which he places the Kaiso deposits of the Lake Albert Rift valley. These deposits contain a fauna which, on Hopwood's palæontological divisions of the East African Pleistocene, can be called early middle Pleistocene.

More recently O'Brien published the results of his archæological work in Uganda, which was carried out with the co-operation of Solomon as a geologist (O'Brien, 1939). These authors claim that the succession of pluvial and dry phases as proposed by E. J. Wayland is of little significance. Solomon thinks that the geological features of the Uganda deposits can be explained satisfactorily by means of tectonic movements (tilting chiefly) causing submergence and emergence, swamping or drowning of valleys and even reversal of the flow of certain rivers. Though O'Brien and Solomon tend to emphasize how much their stratigraphical scheme differs from that of Wayland, they admit on many occasions that climatic fluctuations did occur. Wayland, on the other hand, is fully aware of the influence of tilting and other tectonic movements. It is therefore likely that the two schemes will eventually be merged into one.

The approach taken by O'Brien and Solomon, however, illustrates one of the most formidable difficulties encountered by Pleistocene geology in East Africa, viz. the interference of tectonic movements, mostly connected with the formation of the great Rift valleys. Many of the deposits on which the stratigraphy of the East African Pleistocene is based lie either in the western, Lake Albert–Lake Edward–Lake Tanganyika Rift, or the eastern, Lake Rudolf–Lake Naivasha–Lake Natron–Lake Eyasi Rift. The main phase of formation of these rift valleys was a late event in geological history and connected with a great display of volcanism. It has been regarded as Pliocene or as late as middle-upper Pleistocene.

TANGANYIKA.—The most complete record in any one area of events connecting the history of the Rift with the climatic succession and the evolution of the fauna has been found in northern Tanganyika, under about 3° S. lat., at Olduvai (usually spelt Oldoway). Whilst the human skeleton which Reck excavated at this locality in 1913 (Reck, 1914) is now regarded as a burial placed into the relatively early horizon (2) in later times (Leakey, Reck, Boswell and Hopwood, 1933; Leakey, 1936, p. 172), the sequence of deposits, which totals 80–100 m., has been checked and confirmed by a number of experts and found to be as follows (beginning with the latest):

(5) Terrestrial, often loess-like, deposits covered by steppe-lime, a soil of a concretionary nature.

(—) Unconformity, representing a time of erosion during which valleys were cut into the preceding lake deposits.

(4) Volcanic tuff, deposited or redeposited in water.

(3) About 15 m. of red, tough rock, containing lenses of pebbles. Deposited in water.

(2) Volcanic material, similar to (4), 12 m. thick.

(1) Very thick basal complex, of numerous layers of volcanic tuff, apparently deposited on land.

The view is generally held that the lake deposits (2 to 4), were laid down

during a major pluvial. The lake was succeeded by a major phase of faulting, which lowered part of the adjacent country and initiated the period of erosion which intervened between (4) and (5). Reck (after 1930) considers this late period as the chief period of formation of the Rift valley, whilst other workers, though admitting the importance of this tectonic phase, still regard the main faulting, which produced the first rifts, as pre-Pleistocene.

In recent years the Olduvai series has been extended into the past by the terrestrial Laetolil Beds found south of the Olduvai gorge, towards Lake Eyasi. These beds are subaerially deposited volcanic tuffs, and contain an exclusively terrestrial fauna, including an elephant which is more primitive than the form of *E. antiquus* encountered in the Olduvai series (*Elephas* aff. *planifrons* Falc. and Caut.). The area of the Laetolil Beds has been studied in detail by Kent (1941), and its contained elephants have been described by MacInnes (1942). Kent's summary is of particular value because it relies on a greater amount of geological research, considering the several expeditions which worked in the area and the working out of their results (compare Hopwood, 1933), than the stratigraphical sequences proposed for other areas in East Africa.

East Africa: Summary.—The evidence for climatic fluctuations in the Pleistocene of East Africa is as promising as it is, as yet, unsatisfactory. The chief difficulties are (*a*) that of establishing a detailed relative chronology of climatic changes based on single sections or localities, and (*b*) that of correlating the localities with one another.

It may be argued that (*a*) has been successfully overcome in several places, but it appears to me that more attention will have to be paid to the *climatic* character of the deposits. In areas, for instance, where lakes were formed by faulting, lake deposits in a section need not signify a pluvial, and in a tropical climate with a dry season lasting for several months, wind-borne dust-deposits need not indicate desert conditions. The study of buried soils will probably help here, too, as it has done in Europe.

As regards (*b*), correlations can be based either on the succession of climatic events, on tectonic phases, on the contained human artifacts, or on the fauna. Relying on the climatic sequence means, in view of the difficulty (*a*) to rely on something the regional character of which we are hoping to establish, and the same applies to the succession of human industries. Both, therefore, should be excluded, at any rate for the time being. Tectonic phases are most helpful, especially in correlating over short distances, but whether certain phases of rift formation were absolutely contemporary relative to the suspected pluvial phases, for instance, in Kenya and in Tanganyika, is difficult to prove. I am inclined to think, therefore, that, although work on tectonic phases and on pluvials has to be continued and intensified, the only halfway reliable stratigraphical clue to the East African Pleistocene is provided by palæontology. As in Europe, so in East Africa, do the mammalian faunas indicate the approximate level in the Pleistocene. In Europe, the lower, middle and upper Pleistocene can be distinguished by means of the associations of species occurring in the respective beds (p. 175); in East Africa a corresponding division is possible, though the lower, middle and upper groups in East Africa need not be, and probably are not exactly contemporaneous with those in Europe.

For East Africa, however, such divisions based on the evolution of the fauna provide a means of classifying stratigraphically any deposit containing a fauna. A detailed relative chronology cannot be arrived at in this way, but it is certainly advisable to obtain a general idea of the relative ages of the deposits before proceeding to a more detailed correlation.

Most of the palæontological work has been done by Dr. A. T. Hopwood, who most kindly contributed the following lines summarizing the palæontological evidence so far obtained from the Pleistocene of East Africa:

" The three divisions of the East African Pleistocene may thus be defined.

"*Upper Pleistocene*, containing the modern fauna, with the African Elephant as a late invader from outside the area.

" *Middle Pleistocene*, with *Elephas antiquus recki* and *Hippopotamus gorgops*. Chalicotheres, Mastodonts and Deinotheres are occasionally found; they are survivals from earlier times.

" *Lower Pleistocene*, containing *Stegodon*, primitive elephants of the *planifrons-meridionalis*-type, and two species of *Hippopotamus*, namely, *H. gorgops* and *H. imaguncula*. Mastodonts and Deinotheres are not infrequently found, but Chalicotheres are rare.

" One or two genera of the *Hipparion*-group and one or two species of zebra occur throughout the Lower and Middle Pleistocene, but only the zebras continue into the Upper Pleistocene.

" The Upper Pliocene has not yet been recognized anywhere in the area."

B. CLIMATE AND RADIATION IN THE TROPICAL ZONE.

Pleistocene geologists tend to regard the equatorial zone as one whole, and the apparent fluctuations of the climate during the Pleistocene as contemporaneous within the limits of the equatorial zone. Some workers have gone further and correlated these fluctuations with those of the Mediterranean zone (Nilsson, etc.) or even with the glacial and interglacial phases of Europe (Leakey, etc.). This procedure is based more on wishful thinking than on evidence proving contemporaneity. *A priori*, there is no reason why pluvials of the tropical zone should, or should not, be contemporaneous with those of the Mediterranean or with the glacials of Europe, and the deplorable fact that evidence regarding this point is completely lacking is most generally overlooked.

It is useful, therefore, to see what the astronomical theory suggests. The most obvious questions arising are (*a*) do the fluctuations of solar radiation in the tropical zone support the idea of pluvials, and (*b*) if so, do the radiation curves suggest contemporaneity of equatorial pluvial with European glacial phases? Furthermore, if the answers to (*a*) and (*b*) are unsatisfactory, (*c*) does the astronomical theory suggest an alternative explanation of the climatic fluctuations in the tropics?

Fluctuations of Radiation in the Tropical Zone.—(*a*) The radiation curves for the summers of 5° N. and 5° S. lat. show fluctuations which are exactly opposed, a summer with increased radiation on 5° N. corresponding to one with decreased radiation on 5° S. But since north-summer and south-summer differ by a period of 6 months, it is the winter-curve of the southern latitude which coincides in time with the summer-curve of the northern latitude. These two curves resemble each other so much that we can safely

select the summer-curve of 5° N. for the radiation received by the equatorial zone in the summer half-year of the northern hemisphere (approximately

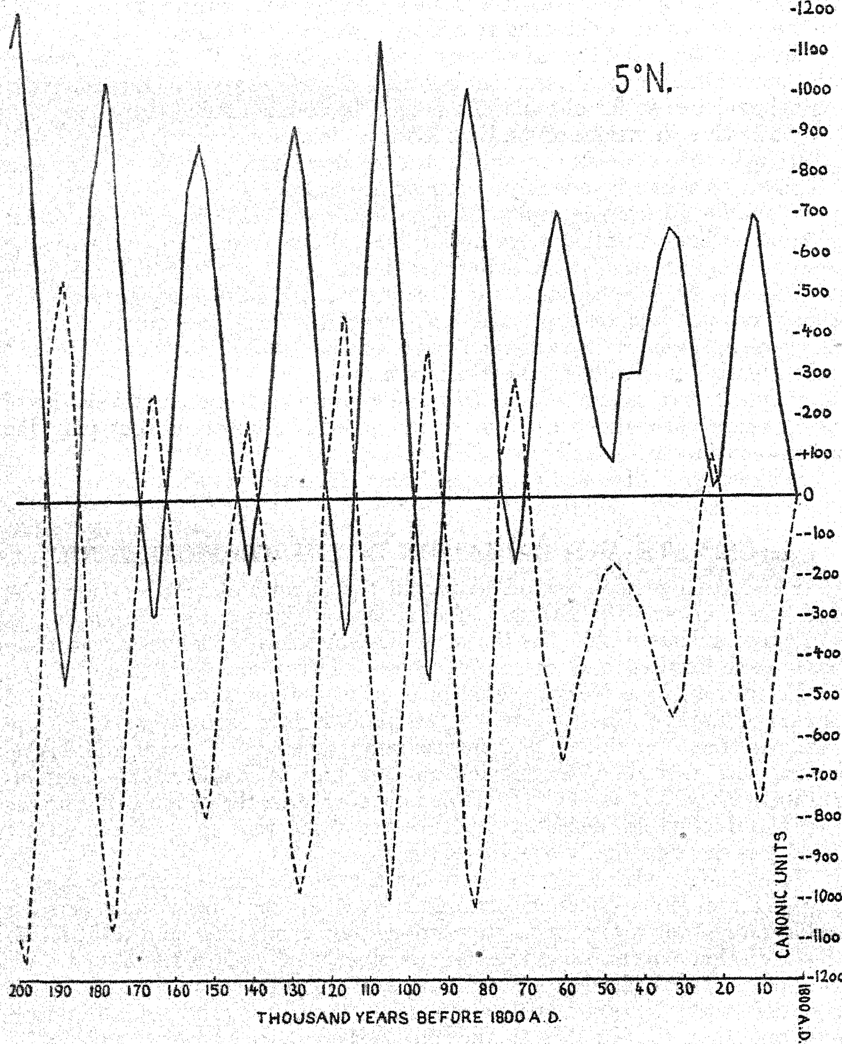


Fig. 67.—Summer (full line) and winter (broken line) radiation on 5° N. lat. for the last 200,000 years. Based on tables by Milankovitch (1938*a*, *b*). (The rectangular kink of the summer curve at 45,000 B.P. is perhaps due to a misprint in the table. This cannot be ascertained for the time being.)

April to September) and the summer-curve of 5° S. for the winter half-year of the northern hemisphere (approximately October to March).

The summer-curve of 5° N. (Fig. 67) shows that, at certain times during the Pleistocene, over 1000 canonic units were received in excess of the present amount, whilst at other times a deficit occurred which rarely exceeded 600 canonic units. Thus, the amplitudes of the fluctuations of solar radiation in the equatorial zone were 50 to 100 per cent. greater than in temperate Europe.

The effect on the equatorial climate of these fluctuations has not yet been worked out. It is a presumably difficult task which awaits a tropical meteorologist. For the time being it is impossible to say how an increase or decrease of seasonal radiation would modify the present equatorial climate and, in particular, which conditions might produce the appearance of a pluvial in geological deposits.

If, however, one assumes that the periodical increase or decrease of seasonal radiation did cause the pluvial phases, one can hardly escape the conclusion that there were about 28 pluvial phases during the last 600,000 years, for this is the number of maxima (or minima) of summer radiation in the equatorial zone.

The geological evidence with its two or three major pluvials does not particularly point in this direction, though one has to keep in mind that even in Europe fifty years of stratigraphical research were required to establish the detailed relative chronology of the Pleistocene. The numerous lake levels found by Nilsson for the upper Pleistocene of East Africa are the only conceivable expression of frequent oscillations, but their descending order is not in good agreement with the radiation curve (compare the last maxima in Fig. 67 with Fig. 65).

Problem of Contemporaneity of Pluvial and Glacial Phases.—(*b*) Whilst question (*a*) thus has to remain unanswered, the question (*b*) of the contemporaneity of equatorial pluvials and European glacials can be more satisfactorily dealt with.

A glance at the radiation curves for, say, 5° N. and 75° N. shows that only some of the numerous oscillations of the tropical curve coincide with some of the relatively few oscillations of the arctic curve. If, therefore, the tropical pluvials do depend directly on oscillations of solar radiation, contemporaneity with a glacial phase will occur in exceptional cases only. And if the pluvial phases of the tropics depend on factors other than radiation, contemporaneity is even more unlikely.

Thus, it has to be admitted that neither the interpretation of the major pluvials nor their correlation with the glacial phases of Europe can, for the time being, be based on the radiation curves directly. There is a slight chance, however, that the minor oscillations evidenced by Nilsson's lake levels can be dated eventually by means of the radiation curves.

Caloric and Meteorological Equators.—(*c*) Fortunately the astronomical theory suggests another possible source of the fluctuations of the tropical climate between dry and wet. This is the periodical movement of the caloric equator.

It is well known that the belt of the calms or of rising air of the tropical zone lies a few degrees north of the geographical equator (average about 5°, more on continents, less over the oceans). The cause of this asymmetry has generally been sought for in the more intense circulation of the atmosphere of the southern hemisphere, owing to which the belt of the equatorial

calms lies nearly everywhere slightly north of the geographical equator. This belt of the calms is called *meteorological equator*.

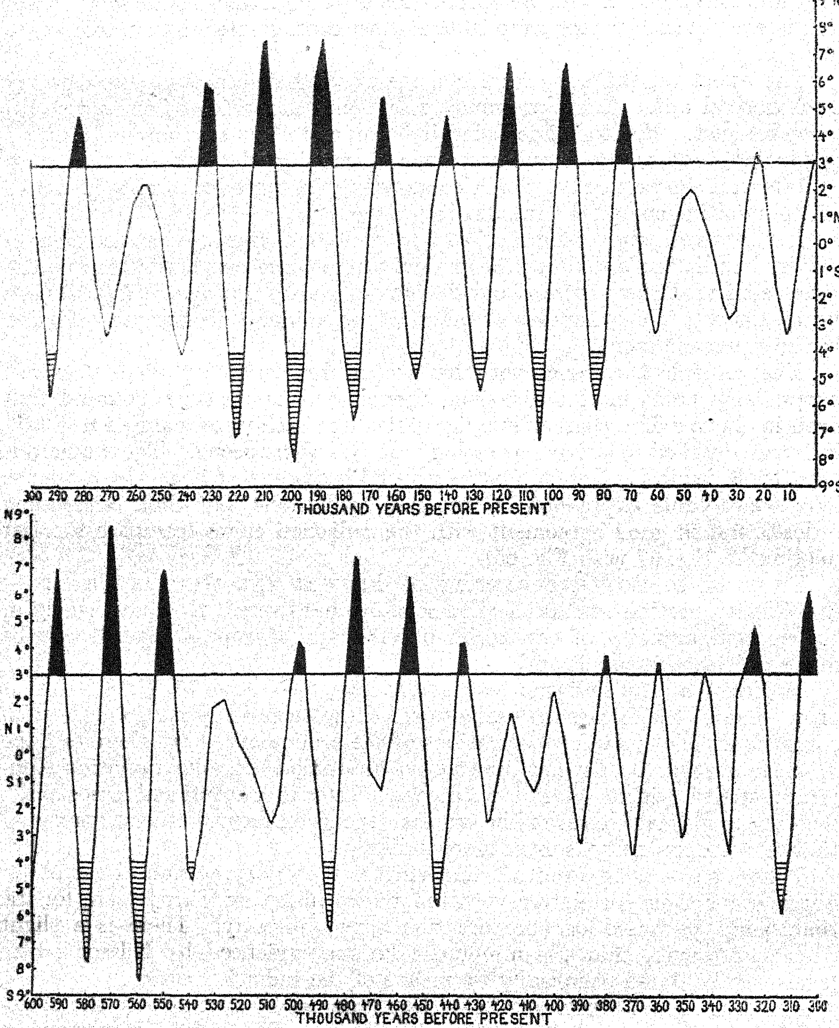


FIG. 68.—Positions of the caloric equator relative to the geographical equator for 600,000 years B.P. Horizontal line, present position. Black: phases of displacement north of present position. Hatched: phases of displacement south by more than 7 degrees from the present position. Based on table in Milankovitch (1938*b*, p. 662).

Now, Wundt (1934, 1937) has been able to show that this purely meteorological explanation is not exhaustive, and attributes part of the northward

displacement to the position of the belt of minimum annual fluctuation of radiation, which at present lies at about 3° N. This belt is called the *caloric equator*.

The position of the caloric equator, which is considered as a contributory cause of the meteorological equator not only by Wundt, but by Spitaler also (1934), is not stable. Its changes have been calculated by Milankovitch (1938*a*, *b*); they are here given in the form of a graph (Fig. 68).

If, then, the position of the meteorological equator and with it that of the equatorial zone with two rainy seasons depends on the position of the caloric equator plus the displacement produced by the more intense circulation over the southern hemisphere, the position of the caloric equator at any moment during the Pleistocene will give us a rough idea of the position of the climatic zones of the tropical belt. Expressed differently, a northward displacement of the caloric equator from its present position at 3° N. lat. will bring increase of rainfall to those latitudes which now lie on the northern outskirts of the belt of tropical rains, such as the Sudan, whilst a southward displacement will have the reverse effect. On the southern outskirts, however, the same displacement will bring drier climate, whilst the southward displacement will bring more rain. The effects of the movements of the caloric equator are opposite on the two hemispheres.

The effects within the zone of tropical rains are difficult to estimate. A locality will pass from the belt with two rainy seasons into one of the belts with one rainy season, or *vice versa*. It is of very little use to speculate further on these effects; they will have to be worked out by a competent meteorologist.

It is apparent, however, that the movements of the caloric equator have to be considered as a possible, and perhaps very important, cause of climatic fluctuations during the Pleistocene. Periods during which the caloric equator lay, at frequent intervals, farther north than at present are marked in black on the diagram (Fig. 68).

Their grouping is not entirely unlike that of the pluvial phases of Kenya and Uganda as suggested by Leakey and Wayland, so that the climatic significance of the caloric equator certainly deserves a closer study.

SUMMARY: TROPICAL ZONE.—The main purpose of the preceding survey of the tropical zone of Africa and of the possibilities of dating suggested by the astronomical theory lies in the warning it sounds to all who are inclined to correlate rashly on insufficient evidence. Whether the astronomical theory is applicable to the tropical zone or not, much geological work is needed first, in order to establish local climatic successions. In doing so, one has to keep one's mind free from preconceived ideas like the contemporaneity of tropical pluvials and glaciations with the glacial phases of Europe, and the climatic significance of the various types of tropical Pleistocene deposits has to be established also. Much promising work lies ahead here, but it will require a good deal of patience before detailed correlation can be successfully carried out.

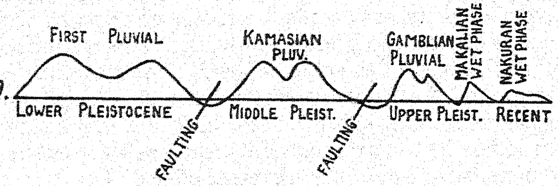
Independently it will be necessary to enter upon a study of the theoretical modification of the tropical climate by the fluctuations of solar radiation and by the movements of the caloric equator, if such work is at all possible at the present stage of tropical meteorology.

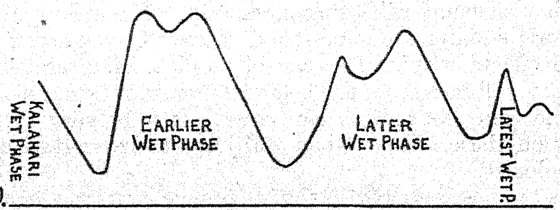
It is probable that before this programme can be carried out, some

measure of correlation will be achieved by means of the ubiquitous high sea-levels of the Pleistocene (see Chapter IX).

c. SOUTHERN AFRICA.

RHODESIA.—At the southern edge of the tropical zone, a succession of climatic phases has been worked out for the district of the Victoria Falls (Armstrong, Jones and Maufe, 1936 ; Cooke and Clark, 1939). Cooke and Clark arrived at a series of dry and wet phases (Fig. 70), which resemble in some respects those of South Africa. Malan (1943) rightly remarks that





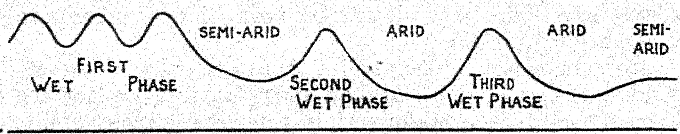


FIG. 69.—Fluctuations of rainfall intensity in Kenya, according to Leakey (1936).
FIG. 70.—Fluctuations of rainfall intensity at the Victoria Falls, Rhodesia, according to Cooke and Clark (1939).
FIG. 71.—Fluctuations of rainfall intensity in the Vaal River Basin, South Africa, according to Söhnge, Visser and van Riet Lowe (1937). Earliest wet phase, preceding the so-called " First," not shown. The superposition of Figs. 69 to 71 does not imply a correlation of the pluvial phases of the three areas.

this serves " to bring home to us the dangers of assuming too wide a geographical extension of the climatic sequence established for any particular confined geographical area."

SOUTH AFRICA.—On entering the Union of South Africa we reach a country more promising than any other country outside Europe. It lies in the climatic belts which correspond, on the northern hemisphere, to the dry belt of the Sahara and to the Mediterranean zone. The dry belt of South Africa is much less pronounced than that of the Sahara, and large portions of it receive a fair amount of rainfall in summer. The summer maximum of this region, which covers the Transvaal and the Orange Free

State about 25° S. lat. where the geological work to be mentioned presently has been carried out, links it with the tropical zone with a single rainfall maximum as exemplified by Rhodesia.

In the extreme south, however, as exemplified by Cape Town (34° S. lat.), the climate is of the Mediterranean type, with the rainfall maximum in winter and with a dry summer. A theory of the climatic fluctuations in South Africa has to take into account the existence of these two types of climate.

THE VAAL RIVER SURVEY.—The succession of human industries in relation to climatic phases has been the subject of a comprehensive survey organized by the Bureau of Archæology and the Geological Survey of South

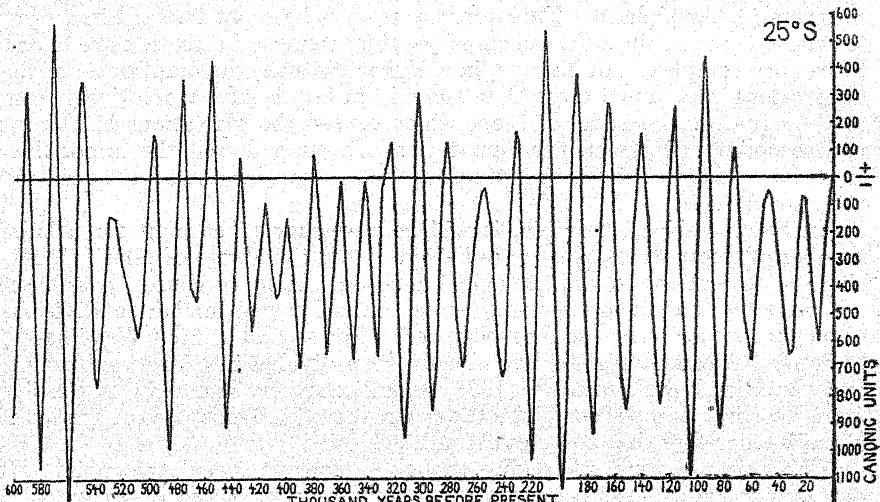


FIG. 72.—Curve of summer radiation for 25° S. lat. Based on tables by Milankovitch (1930).

Africa (Söhnge, Visser and Van Riet Lowe, 1937). These authors studied a portion of the valley of the Vaal with its terraces and sub-aerial deposits. An earliest pluvial is evidently composite, since while on the whole erosion prevailed, deposits of "Older Gravels" were aggraded from time to time (van Riet Lowe, 1938, p. 439). An extinct species of elephant comes from this complex.

The earliest pluvial was succeeded by a dry phase (deposition of the Kalahari Sand), after which the so-called First Wet Phase witnessed the formation of the Younger Gravels (Fig. 71). This pluvial has been divided into three phases. Two further wet periods have been distinguished. The final phase indicates a slight increase of dampness.

RADIATION CURVES FOR SOUTH AFRICA.—Fig. 72 gives the summer radiation for the latitude of 25° S., approximately that of the Vaal River Valley. It will be noticed that, at present, the Vaal area enjoys a relatively high amount of radiation in summer (coupled with a relatively low amount in winter), and that on the whole during the Pleistocene summer radiation

was lower (and winter radiation higher) than nowadays. The climatic effects of these deviations have not yet been worked out, though this is no doubt possible.

The minima of summer radiation, or times of small differences between summer and winter, are always coincident with phases of an extreme southerly position of the caloric equator. The latter fluctuation may conceivably have brought more summer rainfall to the Vaal Basin, incorporating it temporarily in the belt of tropical rainfall; it was very considerable at times, attaining twice in the last 600,000 years to more than 11 degrees of latitude and not less than 15 times more than 7 degrees (see Fig. 68). The coincidence with a southerly position of the caloric equator of summer minima of radiation may have reduced evaporation, the two factors together resulting in a wet phase. This interpretation is here put forward in a most tentative manner, since the effects of the fluctuations of radiation are bound to be very complex. In Europe, in a higher latitude, the amplitudes of the fluctuations vary much more than they do in South Africa, relatively close to the equator, and some of them which caused the glaciations in Europe had secondary effects on the climate which overshadowed the minor fluctuations. This overshadowing of minor fluctuations need not have occurred in South Africa.

In South Africa, therefore, it will be necessary to account for a large number of fluctuations of solar radiation, leaving evidence of relatively few climatic oscillations in the geological deposits. It is, of course, possible if not probable that future geological research will reveal further subdivisions of the four major phases so far recognized. The second (" First Wet Phase " of South African geologists) has already been divided into three subphases, and van Riet Lowe's remarks (1938) suggest that the same will be possible for the earliest, the period of the Older Gravels. The existence of groups of pluvials, therefore, has to be explained.

This raises a very interesting though somewhat speculative point. If the assumption is correct that the wet phases were those of an extreme southerly position of the caloric equator coupled with small seasonal differences of radiation, the curves (Figs. 68 or 72) show clearly periods during which such conditions were particularly intense at frequent intervals. There were four or five periods of this kind, between 80,000 and 225,000 (with a phase of less intensity in the middle), between 290,000 and 315,000 (a relatively weak period), between 440,000 and 490,000 and between 435,000 and 600,000 B.P. I do not wish to say that this suggests any particular correlation of the geological evidence from the Vaal River with the radiation curves, but it certainly opens up a way for further chronological studies.

It may be objected that the periods mentioned were, at the same time, periods when the caloric equator frequently moved into extreme northerly positions and when the radiation attained extreme seasonal differences. This is certainly true, but the effects of these deviations from the present-day conditions were much smaller than those of the southward movement of the caloric equator and of the summer minima of radiation. The northward movement of the caloric equator exceeded 5 degrees of latitude only once (its southward movement exceeded 11 degrees twice), and the summer maxima of radiation exceeded + 500 canonic units only twice, compared

with 26 minima of − 500 to − 1200 canonic units. One appears to be justified, therefore, in laying greater emphasis on the southward movements of the caloric equator and the summer minima of radiation.

Moreover, it may be that extreme northerly positions of the caloric equator extended the zone of winter rains which is at present confined to the extreme south of South Africa to lower latitudes. This is another meteorological problem which requires examination.

In concluding these speculations on the astronomical theory as applied to the South African Pleistocene it is worth mention that, for the last 10,000 years, summer radiation has been on the increase and the caloric equator moving away from South Africa. In accordance with the interpretation here proposed, this would mean increasing desiccation. This movement, however, came to a standstill at about A.D. 1200, and both curves are now returning from the minor maximum of this date.

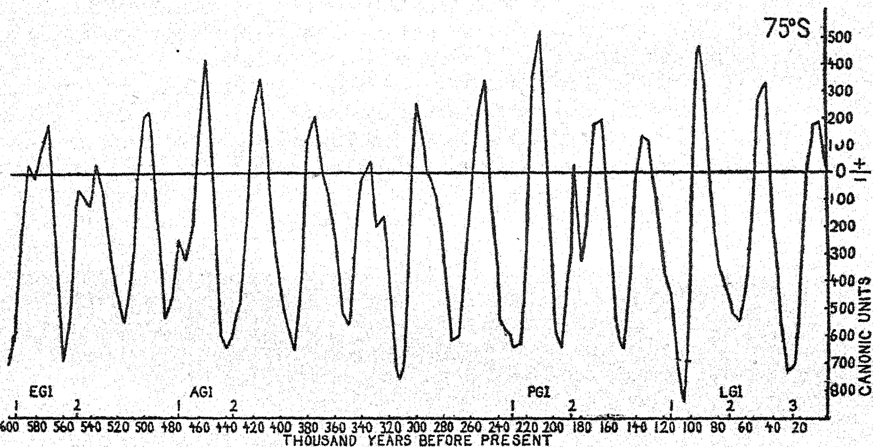


FIG. 73.—Curve of summer radiation for 75° S. lat. Based on tables by Milankovitch (1930).

D. ANTARCTICA.

Finally, the glaciation of the Antarctic continent has to be discussed briefly (Zeuner, 1938). The radiation curve for the summers of 75° S. lat. (Fig. 73) reveals that a minimum which occurred about 10,000 years after the minimum of LGl_1 of the northern hemisphere (in 105,100 B.P.) was the most intense of all. Since the excess of ice during the Last Glaciation over the present volume was, according to Daly (1935, p. 46), 4 million cubic kilometres, the present amount being 12 million cubic kilometres, it appears that the excess of ice accumulated on Antarctica was at no time during the Pleistocene more than one-third of the present volume.

Furthermore, the radiation curve for 75° S. lat. is composed of 17 long periods of intense minima of summer radiation alternating with 17 short periods of weak maxima. It is likely, therefore, that glacial conditions persisted throughout the Pleistocene on the Antarctic continent, and the variations from the present ice-volume never exceeded one-third either way.

The Antarctic glaciation was much more permanent than any other, and its influence on the climates of the southern hemisphere must have been relatively stable. Also, the amount of water released from, or absorbed by, the Antarctic ice-cap, compared with those of other ice-caps, was relatively insignificant. As I undertook to show in 1938, it was of the magnitude of 13 to 17 per cent. of the total of eustatic fluctuation, if one adopts conservative figures, and there is reason to believe that it was usually much less than this.

These conditions, and the lack of other large areas of glaciation, explain why the climatic history of the Pleistocene is dominated by the events that occurred on the northern hemisphere. Through the eustatic fluctuations of the sea-level they exerted a world-wide influence, the chronological significance of which is being realized only gradually. It is necessary, therefore, to pay some attention to this phenomenon.

CHAPTER IX

THE FLUCTUATIONS OF THE SEA-LEVEL AND THE WORLD-WIDE EXTENSION OF THE ABSOLUTE CHRONOLOGY OF THE PLEISTOCENE

A. EUSTASY AND THE ELEMENTS OF ANCIENT SHORE-LINES.

Eustasy.—Eustasy has been the predominant idea in the study of Pleistocene sea-levels. Tectonic uplift or depression of coast-lines, caused by isostatic readjustments, earth-movements connected with volcanism or earthquakes, or mountain-building and allied tectonic processes, have been observed in many places, but these movements are either local or restricted to certain zones. Where ancient shore-lines can be traced horizontally, sometimes over many hundreds of miles irrespective of stratigraphical or tectonic units, it is difficult to assume tectonic movements, and the explanation that they are due to a rise or fall of the sea-level is the obvious one. The fluctuations of the sea-level in Pleistocene times can, in fact, be interpreted satisfactorily by the eustatic theory, and, at least for the lower levels observed, *glacial eustasy* (rise and fall due to repeated release and absorption of water in the ice-caps) explains the observed facts very well indeed. This theory is rather old; it was recently discussed by Daly (1934).

The amount by which the present sea-level would rise if all the ice in existence should melt has been estimated at 40–60 m. (for details see Daly, 1934, p. 12). Ancient shore-lines, which are higher than this, cannot be explained by glacial eustasy. Baulig (1935) has emphasized this difficulty, and suggested that deformation of the basins of the oceans played some part in the process (p. 164). These questions, however, take us back to Tertiary times and even earlier periods of which our knowledge is not detailed enough to attempt chronological correlation. At any rate for the middle and upper Pleistocene the theory of glacial eustasy works well, and it is to these times that the following survey is chiefly restricted.

River-Profiles and Ancient Shore-Lines.—Former sea-levels can be detected either by a study of the profiles of rivers running into the sea, or by the more direct method of investigating the deposits of ancient shore-lines and phases of marine submergence preserved in the vicinity of the present-day coasts.

The longitudinal profiles of rivers have been used by many workers (for instance, Green (1936), Hanson-Lowe (1938), Jones (1924)). A combined study of aggradation terraces and knickpoints, as outlined in Chapter I, enables one to estimate the height of the sea-level at the mouth of the river during certain periods. The method is applicable in the Tertiary and perhaps the early Pleistocene, where considerable allowance can be made for inaccuracies in the reconstructed profiles, the successive levels being

separated by many tens of metres. In the later Pleistocene, however, the observed heights follow one another much more closely, and the margin of error has to be correspondingly smaller.

"RAISED BEACHES."—The term "raised beach" has been applied to almost any feature indicating a sea-level higher than the present. It is not altogether satisfactory. If it is used to describe a eustatic high level, it should not be called "raised," and often the feature preserved is not part of a beach *sensu stricto*, but a submarine deposit, or a fossil dune formed above sea-level, or an abrasional feature. The term "ancient shore-line" would be more correct if restricted to the water-level to which the various deposits and formations refer, these being called what they really are, namely, fossil beach sand, shingle, marine mud or clay, etc.

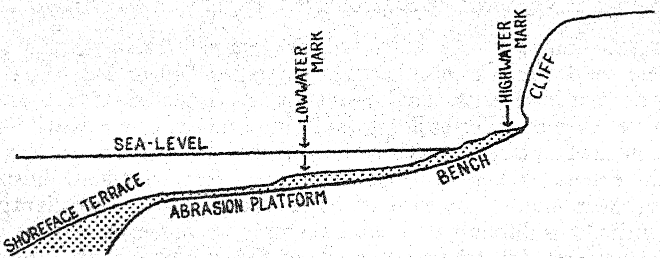


FIG. 74.—Elements of a shore. Cross-section showing erosional features with a thin veneer of deposits. Based on Johnson (1938, Figs. 21, 22.)

Evidence for ancient high sea-levels is afforded by one or several of the following elements:

A. Destructional: Sea-cliff; platform of marine abrasion or wave-cut bench; the notch or undercut, often connected with sea-caves; the line of rock-boring shells.

B. Constructional: Submarine deposits from below low-water mark; beach deposits (sand and shingle, often overlain by dune-sand); pebble- and sand-ridges (storm beaches), bars and spits.

Any one of these may occur in the fossil state, single or combined with others, and if no statement regarding the kind of evidence relied upon is made by an author, any one of these elements may have been used. It is necessary, therefore, to discuss briefly the relations of the formations mentioned to the actual height of the sea-level. Papers have been published which say little or nothing about the way in which the height of the sea-level was determined, and often it is not certain whether high-water level, or mean sea-level, is referred to. Johnson (1931*a*) has made suggestions as to how work on ancient sea-levels should be done properly. His treatise on the evolution of modern shore-lines (Johnson, 1938) is a valuable introduction to the phenomena involved.

DESTRUCTIONAL ELEMENTS OF COAST-LINES.—Of the elements listed above, the sea-cliff and the sloping platform or bench in front of it are well known features of Recent shores (Fig. 74). The undercut at the base of the cliff is more rarely developed. Nevertheless it is important as it is sometimes found connected with ancient shore-lines, and frequently associated with caves containing fossils and the remains of early man.

CLIFF.—Some steep cliffs reach far below sea-level, and they are often very resistant topographical features. The sea being deep immediately in front of such cliffs, the ordinary waves of oscillation (movement of water-particles up and down) are not, or to a small extent only, transformed into waves of translation (movement of particles in the direction of progression of the waves), and the erosional effect is correspondingly small.

On the other hand, cliffs which adjoin a comparatively shallow sea-bottom are exposed to the impact of powerful waves of translation and are cut back more or less rapidly, so that a wave-cut bench is formed. A supposed ancient sea-cliff, therefore, must not be used for determining the height of the former sea-level, unless evidence for the platform, the undercut, or some other unmistakable feature is associated with it.

WAVE-CUT BENCH.—The wave-cut bench, or wave-carved platform,* has been employed most widely as an indication of former high sea-levels. The relation of this platform to the exact height of the water-level, however, is somewhat complicated. Some physiographers believe that it normally does not reach above high-water level. Yet Johnson (1931*b*) has shown that on the coasts of isles in the Pacific the "wave-carved platforms normally have their inner margins from a few centimetres up to two metres or more above the level of ordinary high tides."

In fact, the height of the inner edge of the bench has not everywhere the same relation to the height of the sea-level. On shores with a heavy surf, where the action of waves of translation is intense, the abrading action reaches above the actual water-level, and the platform extends beyond the highwater mark, as was described by Johnson from the Pacific. On a much smaller scale the same feature may be observed on the coast of Essex, where the cliffs consist of London Clay and where the sea is shallow. I observed that the result of a few days of high winds from the sea was an undercut not less than 3 ft. above high-water mark, and the wave-cut bench, where exposed, met the cliff at about this height. This observation bears out Johnson's view, but there are other shores on which the platform is entirely covered by the high-water level.

As an example for this type of coast the Channel Islands may be cited, and Jersey in particular. Here, the often extensive modern benches reach up to high-tide level, but no instance is known to me of their exceeding it. It is probable that the relation of the intensity of the translatory waves to the resistance of the rock and the steepness of the cliff determines whether the wave-carved platform exceeds high-water level or not. Along almost perpendicular, resistant cliffs its inner edge appears to remain well below high-water mark, sometimes by several metres.†

In the Mediterranean Sea the tides are negligible (not more than about 3 ft.). The wave-cut platform is, as a rule, submerged. In bays and in modern sea-caves it remains covered by two or more metres of water, but where wave-action is intense, abraded rock-platforms emerge above sea-level, just as on the coasts of the open ocean.

From such observations it may be inferred that the wave-cut bench is

* Johnson distinguishes from this the "platform of abrasion," this being the deep and permanently submerged continuation of the "wave-cut bench."

† This is the case of a very narrow bench connected with a steep cliff, representing a "youthful" stage of shore erosion.

normally submerged, and, at its inner edge at the base of the cliff, reaches to a little below or above high-water mark or, in a non-tidal sea, sea-level. The margin of error implied in determining the height of an ancient sea-level from the inner edge of a bench is several metres, though it will rarely exceed 4 m.

Edges of fossil benches are frequently exposed in sections parallel to the modern beach. Seaward edges of such benches have provided a vast number of figures for "raised beaches," but they are nearly always too low. It is necessary to measure the height of the *inner edge* of the platform at the junction with the cliff, and this spot is mostly hidden under beach deposits and talus.

High-water Level and Mean Sea-Level.—Another difficulty which has to be borne in mind is that, in a tidal sea, the inner edge of the platform is near high-water mark, whilst measurements, to be comparable, should refer to mean sea-level, both Recent and fossil. For the middle and late Pleistocene times with which we are chiefly concerned, it is safe to assume that the *general* movements of the tidal waves over the earth were the same as now. On open shores, as for instance the south-east coast of North America, they are not likely to have differed much from those observed at the present day in phases with sea-levels moderately higher than that of to-day. In straits, channels and estuaries, however, greatest caution is advised in applying the present tidal range to a fossil shore-line in order to obtain mean sea-level. For the 7·5 m. and 18 m. levels in the English Channel, for instance, which run through the Straits of Dover, tidal conditions are likely to have been similar to those of to-day. For the 32 m. level of the same region this is less certain; but the deviation is likely to have been small. But for any sea-level *lower* than the present, the configuration of the coast-line of the English Channel cannot be assumed to resemble the present one, and the tides must have been very different. Each case, therefore, has to be critically studied, before half the (present) tidal amplitude is deducted from the observed high-water mark of a fossil shore-line, in order to obtain mean sea-level of the Pleistocene phase in question.

Undercut, Notch, or Groove.—The third erosional feature, which can be of use in the determination of ancient shore-lines, is the undercut, notch, or groove, sometimes observed at the base of a cliff, or in the wall of a cliff. Its height relative to the sea-level at the time of its formation varies with its position.

Undercuts formed at the foot of a cliff extending parallel to the main orientation of the coast-line are entirely horizontal. They are situated where the bench meets the cliff, but they form part of the cliff and therefore are higher than any portion of the bench. They are produced by the scouring action of the translatory waves carrying pebbles and sand, and where cracks or soft portions render the cliff liable to rapid destruction, sea-caves may be formed which are thus directly connected with the undercut. This is why sea-caves play an important part in the work on ancient shore-lines.

Undercuts in the position just described define the high-water mark (or mean water level in a tideless sea). Their exact height is controlled by the same factors as is that of the inner edge of the bench (p. 227), and they may

lie from slightly above to slightly below the average high-water mark concerned.

There are, however, undercuts which bear no direct relation to the sea-level. They are found in gullies and long caves cutting into the land at right angles to the general direction of the coast-line, or on the sides of promontories. In these cases the rock-walls on which the undercut is being eroded extend parallel to the direction of movement of the waves, the swoop of which is intensified by the narrowness of the passage. The waves carry shingle and blocks which rub against the walls and produce undercuts which, owing to the landward rise of the floor on which the material is moved, rise towards the land, sometimes quite considerably, and mark the line along which the rock-wall meets, or met, the sea-bottom. They may reach above sea-level or high-water mark, but they often lie very much lower. The gully undercut is really a special case of the wave-cut bench rather than of the ordinary cliff-undercut. Its height is of little use in defining ancient sea-levels except that it indicates the minimum height reached by the swoop of the waves.

Horizon of Boreholes of Shells.—A conspicuous feature, especially of certain limestone caves and cliffs in the Mediterranean, is a marked line of perforations made by rock-boring bivalve shells (genera *Pholas*, *Saxicava*, *Lithodomus*, *Petricola*, *Gastrochæna*). These shells are not confined in their activities to the sea-level, but their holes are sometimes found in abundance just below the water-line. Where, deeper down, a fur of calcareous algæ, barnacles and sea-weeds is present, the weakening of the rock by the boring shells is concentrated at or just below the water-line, and an undercut is occasionally formed which may be very pronounced. As a rule, however, the holes are not crowded enough for a groove to be formed. In the Mediterranean, their absence above and presence below the water-line often affords valuable evidence for ancient high levels of the sea, particularly in caves.

Ancient Shore Deposits.—Apart from erosional features, deposits on the beach or close to it have been used widely in the identification of ancient shore-lines. These deposits can be classified roughly into marine (sub-tidal) deposits, ordinary beach deposits (tidal zone), and storm-beach deposits (above high-water level).

Sub-tidal Deposits.—Sub-tidal deposits occur at any depth below low-water mark. They can be distinguished, and to some extent the depth of their formation estimated partly on petrological, partly on molluscan evidence. Generally workers have been careful not to regard as proof of an ancient shore-line this type of deposit, where it occurs above the present water level. It does, of course, indicate a submergence and gives a minimum amount for it.

Beach Deposits.—Beach-deposits proper are mostly composed of sand or shingle, but below half-tide level muds are formed where conditions are favourable. In fossil beaches, sand or shingle, or pebbles embedded in sand, found resting on a wave-cut bench, have commonly been considered as formations marking the exact height of the ancient sea-level. They should, however, be used with great caution. Such beach-deposits are frequent between high-water and low-water marks or a little above and below these limits, and the seaward under-currents of the waves and the flow of the ebb-tide may transport beach material to even greater depths.

Mr. E. F. Guiton, of St. Helier, Jersey, has kindly informed me that in Jersey water-worn pebbles reach to at least 2 ft. below spring-tide low-water level. In conjunction with the storm-beaches of the island, a range of at least 52 ft. is thus established for the modern beach material. This amount is certainly exceptional and due to an enormous tidal amplitude, but it reminds one to be careful.

True wave-deposited beach material is often interbedded with dune-sands, and this combination provides valuable evidence for the position of an ancient high-water level. In other cases the fossil beach material is covered by solifluction deposits, coombe rock, head, or loess. Fauna and petrology suggest that these were formed under a cold climate. They usually rest unconformably of the beach beds, though Oakley (1937) has interpreted a section at Slindon, Sussex, as interbedding of beach sand and coombe rock.

Storm-Beaches.—Beach-material, including marine fossils, is thrown up above high-water level by the waves, especially in gales. Distinct pebble or sand ridges on many modern beaches bear witness to this, and so do the spits and bars built up from headlands or across the mouths of rivers. They provide an idea of the maximum height to which marine material can be thrown up. A very striking example is the famous pebble ridge called Chesil Bank, near Portland. It is 16 miles long and 170–200 yards wide, and in its highest part up to 42 ft. (12·6 m.) above high-water mark.

A fossil pebble deposit, therefore, gives little help in finding the height of an ancient shore-line. It may be part of a storm-beach or a residual pebble deposit formed near low-water mark.

Another point must not be overlooked. "Raised beach" deposits resting on fossil platforms, such as occur frequently on our coasts, often consist of pebble sheets laid down during the *recession* of the sea from its highest level.

Height of Ancient Shore-Line Derived from Deposits.—In other words, the greatest caution is advised in deducing the height of an ancient shore-line from pebble deposits. Fortunately, however, they often occur combined with other deposits, or with erosional features. A pebble ridge, for instance, is frequently formed above high-water mark whilst the ordinary tidal beach is sandy. If this combination is found in a fossil beach, it may afford a means of fixing the ancient high-water mark. This combination has been used for instance for the identification of Post-glacial beaches in the Baltic region.

Interbedding of marine with aeolian strata has been mentioned above. Sections of this kind yield an upper limit for the high-water mark, but again it must be remembered that they might date from a recession phase *after* the maximum submergence and therefore need not give us the highest level.

Where the height of ancient sea-levels has been determined without consideration of the principles just outlined, a considerable allowance has to be made for possible inaccuracy. In extreme cases it may amount to 50 ft. or more in a tidal sea. Furthermore, when examining figures in publications, it must be considered whether (*a*) they were measured above average or high-water level, and (*b*) whether they refer to an average height of the fossil shore-line or to its high-water level. If, in spite of these diffi-

culties, the figures obtained so far in different parts of the world agree to a great extent and suggest certain definite stages in the oscillations of the sea-level, these stages have to be accepted as realities, although their exact heights above the present average sea-level may still have to be determined by accurate methods.

B. REGIONAL SURVEY OF EVIDENCE FOR PLEISTOCENE SEA-LEVELS. MEDITERRANEAN AND ATLANTIC EUROPE.

It has been necessary to go into these details in order to convey an idea of the kind of evidence available for ancient shore-lines. It now remains to review some of this evidence from various parts of the world, and to investigate their significance for the problem of dating the climatic phases of the Pleistocene. This regional survey cannot be more than a rough sketch.

MEDITERRANEAN: ALGERIA.—The classical region for fluctuations of the sea-level is the Mediterranean. One of the outstanding works on Pleistocene high sea-levels is that of de Lamothe (1911) on the north African coast. Having carefully scrutinized the evidence in the neighbourhood of Algiers, he distinguished sea-levels at 325, 265, 204, 148, 103, about 60, about 30, and 18–20 m. above the present sea-level. Of these, the four or five highest are likely to be pre-Pleistocene. The 30 m. and 18 m. levels exhibit a molluscan fauna of a warmer type than the present (fauna with *Strombus bubonius*, = Tyrrhenian fauna of Issel). This fauna is invaluable for the correlation of the levels on both sides of the Mediterranean.

ITALO-FRENCH RIVIERA.—While de Lamothe studied the southern coast of the Western Mediterranean, Depéret (1906) investigated littoral and marine deposits of the Italo-French Riviera. In 1918 he summarized his results, which agree closely with those of de Lamothe. He gave, or restricted, names to the shore-lines* as follows:

Sicilian	90–100 m.
Milazzian	55–60 m.
Tyrrhenian	28–32 m.
Monastirian	18–20 m.
Unnamed	7–8 m.

Palaeontologically, the three lowest levels show the warm *Strombus*-fauna. The lowermost (7–8 m.) has always been considered as a phase of the 18 m. level (here called Main Monastirian level), to which it indeed is closely related. For convenience it is here called the Late Monastirian shore-line. The term "Grimaldian" recently proposed by Breuil (1943) is not to be recommended, since the marine deposits of the Grotte du Prince at Grimaldi appear to date from the Main Monastirian phase.

ITALY.—Gignoux (1913) studied the faunas of the marine Pliocene and Pleistocene of Italy and Sicily. He analysed the faunal assemblages and deduced the depths in which they might have lived. The section at

* Note that these terms are used in the altimetric sense. They must not be confused with the palæontological terms Sicilian fauna, Tyrrhenian fauna, which have a wider application.

Taranto, for instance, on the west side of a bay called Mare Piccolo, shows a finely stratified marl covered by a chalky sand with *Strombus bubonius* and other shells of a warmer habit than those composing the present fauna. Littoral species dominate, and forms living in deep water are absent; only a few specimens could have lived as deep as 20–30 m. Adding to this the height of the deposit above present sea-level, one arrives at 30–40 m. for the maximum height of the shore-line of that *Strombus*-sea. This result is in complete accord with physiographical observations, according to which the beach would have been at 35 m. above present sea-level. This is the Tyrrhenian shoreline of Depéret.

The underlying marl, however, contains a very different fauna. There are few species only, but these lived at a depth of at least 70–80 m. The shore-line of this phase, therefore, is likely to be the Sicilian, about 80–100 m. above present sea-level. The separation of the two strata is emphasized in the section (at least locally at the Arsenal where I saw it) by a red sandy band, which perhaps represents a soil formed during one of the low-level phases which intervened between the Sicilian and Tyrrhenian.

Besides the 35 m. level, a 15 m. level with *Strombus*-fauna was observed by Gignoux at Taranto. The 15, 35, 80–100 m. levels and one at approximately 60 m. (not observed at Taranto) were found by Gignoux in many other places. Appreciable deviations from these figures occurred only in tectonically disturbed districts. These figures from south Italy agree closely with those from Algeria and the Riviera.

STROMBUS-FAUNA AND THE PRE-TYRRHENIAN FAUNAL BREAK.—We have already had occasion to describe some of A. C. Blanc's remarkable work on the Italian Pleistocene (Blanc, 1937). In reading his papers, one has to bear in mind that he uses the term "Tyrrhenian" in the palæontological sense, as did Issel (1892), who coined the term for the deposits containing the *Strombus*-fauna. Depéret restricted it altimetrically to the highest shore-line containing this fauna (32 m. level). Blanc (1936*b*) is inclined to regard the Main and Late Monastirian levels as substages of the Tyrrhenian, calling the 32 m. level Tyrrhenian I and the 18 m. level Tyrrhenian II, and the present author followed him in his earlier publications. It will become apparent later on why it is advisable to retain the term Monastirian for the two lowest shorelines (*i.e.* 18 m. and 7·5 m.).

Like Gignoux (1913), Blanc emphasizes that a faunal break occurred after the Sicilian and that the 32, 18 and 7·5 m. levels all contain faunal assemblages of the *Strombus*-type ("Tyrrhenian fauna"). The pre-Tyrrhenian fauna contains, besides Mediterranean species, certain others now restricted to more northerly seas (for instance, *Cyprina islandica**), and a number of Pliocene survivals. This assemblage, the "Sicilian fauna," is found in deposits relating to the Sicilian shore-line of 90 to 100 m. Blanc merges with it the deposits of the Milazzian level (about 60 m.). It may well be that this is correct as far as the fauna is concerned, so that the fauna of the "Milazzian," 60 m. sea-level, would have been of the Sicilian

* The value of this species as a climatic indicator is questionable. It now occurs as far south as Arcachon (44½° N. lat.) and thus overlaps with certain southern species such as *Astralium rugosum*, which is found in the Mediterranean and from the Azores and Canaries northwards to the Ile de Ré (46° N. lat.). Moreover, Jeffreys considers the fossil Mediterranean *C. islandica* as a distinct subspecies.

type in most areas. Unfortunately, however, the fauna at the locality Milazzo is nondescript and contains neither typical Sicilian nor Tyrrhenian species. For this reason, Gignoux (1936, p. 647) refused recognition to the Milazzian stage. It must therefore be emphasized again that the Milazzian, as a stage of high sea-level, is well evidenced, and that the sea-level may have fluctuated more quickly than the fauna changed.

The faunal break between the Sicilian and Tyrrhenian faunas is, therefore, of especial interest and highly significant. It will be remembered that the terrestrial faunas of temperate Europe show a similar break, which coincides with the first intense glaciation, *i.e.* the Antepenultimate one. Land faunas of the Antepenultimate Interglacial contain Pliocene survivals and are, from a climatic point of view, somewhat inconsistent, whilst post-ApGl faunas are essentially Pleistocene and climatically more sharply defined. Exactly the same applies to the marine molluscan faunas of the Mediterranean, and one is tempted to ascribe the change from Sicilian to Tyrrhenian fauna to the same cause, namely, the great climatic break caused by the Antepenultimate Glaciation. The evidence relating to the age of the Mediterranean sea-levels within the detailed chronology of the Pleistocene in fact suggests that the deep drop in the sea-level after the time of the Sicilian fauna and before the Tyrrhenian fauna coincided with the Antepenultimate Glaciation.

Late Monastirian Shore-Line.—The 7·5 m. level with a Tyrrhenian fauna, *i.e.* the Late Monastirian shore-line, is well preserved on the Italian coast. Exposures are numerous. Its deposits are often found in caves at this level, for instance, caves of Monte Circeo, Grotta Romanelli, etc.), and horizons of boring shells (*Lithodomus*) are frequently observed at about this height. Issel (1892) mentions them from the Balzi Rossi caves at Mentone and eight other localities at heights from 6 to 10 m. This Late Monastirian shore-line is a distinct feature which must not be disregarded. It is not confined to the Mediterranean.

The evidence from the Lower Versilia (p. 182) suggests that during the Last Glaciation, most probably LGl_1, the sea-level was at least 90 m. lower than at present. Blanc (1936*a*) examined the various estimates made elsewhere for this recession and arrived at − 100 m. as the most likely figure. A submerged platform is found in several parts of the Mediterranean at this depth.

Boule (1919), however, found reason to believe that a drop to − 200 m. occurred at some time. If − 100 m. is the figure for the Last Glaciation, this greater recession may be referable to the Penultimate or Antepenultimate Glaciation, during which one would expect a lower sea-level because of the greater amount of water locked up in the ice-sheets.

Atlantic Coasts of Europe.—The great question in the correlation of sea-levels is whether the shore-lines observed in the Mediterranean are found on the coasts of the open ocean also. Depéret (1918) has answered it in the affirmative, but other workers have remained sceptical. The following account will show that Depéret's and de Lamothe's views are correct, if one excludes from consideration those areas in which isostatic movements have possibly or certainly taken place. In Europe, Scandinavia, the North Sea, the northern part of Britain, and Ireland have to be excluded, in America the east coast north of New York. In Europe the chief remaining

areas are the Atlantic coasts of Portugal, Spain and France, and the English Channel.*

JERSEY.—The English Channel Islands, Jersey in particular, afford instructive evidence. Here, the "raised beaches" are obvious and have been studied for many years. Mourant (1933, 1935) has recently investigated them again, checking many heights and thus contributing to the delimitation of the ancient shore-lines.

SOUTH HILL LEVEL, 33 M.—The highest level preserved is that of South Hill, St. Helier, Jersey. Naish (1919) mapped it carefully and determined its height at many points.

There is a platform rising from 122 ft. to 128 ft., and a groove in a low cliff. Pebble deposits reach up to 138 ft. If one regards the groove as an undercut indicating high-tide level, the high-water mark would have been at about 38 m. Assuming that the amplitude of the tides was much the same in those times as to-day, namely, 7–11 m., about half this amount has to be deducted to obtain the average sea-level to which the South Hill platform belonged. The resulting figure is 33 m.; it agrees excellently with values for the Tyrrhenian shore-line obtained elsewhere. As usual, the height of the deposits exceeds high-water level. They are probably a storm beach formation, and consist of coarse pebbles and shingle embedded in a cemented clayey gravel. The pebbles are soft and decayed, thus differing from those of younger beaches.

The cave Les Thielles in Guernsey (Colenette, 1916), at 125 ft., may belong to the same shore-line. This is likely to apply also to two further localities in Jersey, on the east side of South Hill (Mourant, 1935; 103–114 ft.), and near St. Clement's Church, where pebbles rest on a platform and are covered with head. The platform is about 85–100 ft., but according to Mourant, the deposits extend to 110 ft. or more.

JERSEY, 18 M. SHORE-LINE.—The next lower group of shore-line deposits and marks of abrasion ranges round about 60 ft. O.D. There are about a dozen localities in Jersey and 19 in Guernsey (Colenette, 1916) which are likely to belong to this group. In Guernsey the lowest occurs at 54 ft., the highest at 75 ft. In Jersey the lowest figure is 52 ft., at the mouth of the Belle Hougue cave (Mourant, 1933).

Another locality of the 60 ft. level is the Cotte à la Chèvre, a cave with an undercut of the gully type (p. 229) produced by large boulders at the bottom. On the other hand, high-water level was probably not higher than the entrance of this cave (about 12 ft. high, measured from the top of the boulder deposit). The bottom of the cave is, according to Mourant, 56½ ft. above mean tide, so that 68½ ft. would be the probable upper limit for the high-water level during the formation of the cave. Deducting half the tidal amplitude, one arrives at 53½ ft. (16 m.) for the mean sea-level of that phase. This is only slightly below the usual height of the Main Monastirian shore-line (18 m.).

Other localities of the 60 ft. beach† are marked by exposures of pebbles,

* For Portugal, the presence of the Sicilian (80–100 m.), Milazzian (45–65 m.), Tyrrhenian (20–40 m.), and (chiefly Late) Monastirian (mostly below 12 m.) shore-lines has been established quite recently by Breuil, Vaultier and Zbyszewski (1943) and by Zbyszewski (1943).

† The Cotte de St. Brelade, often erroneously attributed to the 60 ft. level, has afforded no evidence for a marine deposit (Zeuner, 1940b) and is therefore omitted here.

ranging from 59 to 62 ft. above O.D.* At Le Pinacle, a promontory on the west coast, a smoothed shallow groove is to be seen at 61 ft. O.D. (measured by Mourant, 1933). As it lies on the side of the neck which connects the Pinacle rock with the mainland, this notch need not be a typical undercut. There are several Recent *marmites* (marine pot-holes) very close to this place, and the fossil groove might well be the remainder of a marmite active at the time of the 60 ft. beach.

JERSEY, 7·5 M. SHORE-LINE.—The so-called 25 ft. raised beach is so frequently preserved around the coasts of Jersey that only a few localities of special interest need be mentioned here. Pebble deposits are abundant at heights averaging about 25 ft. O.D., but reach up to 45 ft. in continuous sections.

At Les Rouaux near Belle Hougue Point and at Côtil Point, both on the north coast of Jersey, wide platforms with undercuts are preserved in such a position that they may be accepted as marking high-water level. Their exact heights, however, have not yet been determined. Platforms are found in many other places. Some begin only about 20 ft. above mean tide level, but they reach up to 30 ft. or more. Assuming that the sea-caves of the period of the 25 ft. sea were similar to those of the present sea, one can consider the bottom of a cave as beneath high-water mark. The bottom of the 25 ft. deposits is clearly identifiable in many caves in which the conglomerate, with traces of the rock ledge, forms the roof of a modern cave. Using these to determine the *minimum* height of the average sea-level during the 25 ft. phase, one obtains about 5–6 m. above O.D. This minimum agrees satisfactorily with the height of 7·5 m. accepted elsewhere for the shore-line of this phase.

INTERGLACIAL AGE OF THE 7·5 M. LEVEL.—Jersey affords evidence for the interglacial age of this shore-line. Its geological age has been under discussion for some time, because of a supposedly Pliocene fauna of shells and mammals found in a gravelly deposit forming the 25 ft. level in the Belle Hougue Cave.

The fauna comprises a species of deer which has been suspected of being Pliocene, and this, in conjunction with the misconception of a preglacial 25 ft. beach in the south of England, has led some workers to regard this level as possibly Pliocene, and older than the 60 ft. level. In re-determining the mammalian remains of the Belle Hougue cave I have convinced myself that the deer is an insular race of the ordinary red deer (*Cervus elaphus jerseyensis* Zeuner, 1940*a*, *c*). An interglacial age is therefore probable.

The shells found in this deposit were re-determined by Baden-Powell (appendix to Zeuner, 1940*c*). All belong to the Recent Jersey fauna except *Astralium rugosum*, a large top-shell of southern distribution (see footnote, p. 232). It indicates a temperature of the water warmer than now, and recalls the warm Tyrrhenian fauna found at the same altimetric level in the Mediterranean.

The interglacial age of the 25 ft. deposit in the Belle Hougue cave is indirectly confirmed by numerous other exposures in which pebble deposits are covered by accumulations of head and loess, which were formed under

* Pebbles occur at Rouge Nez Point 73 ft. high, and at Verclut Corner at 80 ft. These poor exposures may belong to either the 100 ft. or the 60 ft. level.

a cold climate. At Portelet Bay, the pebbles and boulders of the 25 ft. beach, resting on a loess, are covered by many metres of fine-grained head which, in parts, is almost a pure loess. This section was first described by Lawson (1914); it proves the interglacial age of the 25 ft. level. It further shows that an Older Loess (of at least PGl age) exists in Jersey.*

The head which covers the 25 ft. deposits all round the Portelet peninsula and in many other parts of Jersey is mixed or interbedded with another loess which is an equivalent of the Continental "Younger Loesses" of the Last Glaciation. Sinel (1923) suggested that a land-surface subdivided it into two at Belcroute Bay, but this has not been confirmed, and the sections are no longer well enough preserved to check his claims.

The Pleistocene shore-lines of Jersey have been described at some length because they supply good evidence for the occurrence of the 32 m., 18 m. and 7·5 m. levels of the Mediterranean in the Atlantic area under very similar conditions. At least the 7·5 m. level proved to be plainly interglacial and somewhat warmer than the present sea. A most important argument is thus obtained in favour of a world-wide correlation of Pleistocene sea-levels. For the moment, at least the Tyrrhenian, Main and Late Monastirian shore-lines appear to be present on the Atlantic as on the Mediterranean coasts. We shall now continue our survey to see whether this correlation can be extended to other parts of the earth.

Coasts of North and West France.—The French coast of the English Channel provides plenty of evidence for the Pleistocene sea-levels known to us from the Mediterranean and from Jersey. The classical work is again by de Lamothe (1916, 1918), who studied the terraces of the Somme near its mouth and the traces of marine platforms preserved in the neighbourhood. He found levels corresponding to shore-lines at 103, 56–59, 32–33 and 18–19 m. These figures are almost identical with those for the Mediterranean (p. 231). In 1918 Depéret summarized the work done by Bigot, Gosselet, de Lamothe and others in a well-known paper which wholly supports de Lamothe's conclusions. In 1924 Dubois published his monograph of the Flandrian, to which we shall have to return later on. These publications contain much information also concerning the Atlantic coast of west France. Wherever traces of beaches are preserved, they can be referred to one of the shore-lines enumerated above.

It is interesting to note that the Tyrrhenian level (32 m.) is observed at Wissant and Cape Gris Nez, between Boulogne and Calais. The Straits of Dover, therefore, existed during that stage.

The 18 m. or Monastirian terrace is most conspicuous and is widely distributed. On the west coast of Normandy it contains large erratics from the Channel Islands and elsewhere (Bigot, 1930). In Picardy, at the mouth of the Somme, it connects with certain deposits of this river (p. 81).

Dubois (1924) re-described the important deposits of Sangatte, near Calais. In this locality the cliff-coast of the English Channel recedes and the Flandrian plains begin. Dubois considers the high-level beach deposits of Sangatte as Monastirian, as they refer to a shore-line of a little under 20 m. Their marine fauna resembles that of the present day, or is very

* The Cotte de St. Brelade shows the same loess (Zeuner, 1940*b*).

slightly cooler.* Coastal morphology and sea-currents were much the same as at present. The fossil beach of Sangatte is covered by a coombe rock or head containing an evolved race of the mammoth. Sangatte lies 15 miles east of the narrowest point of the Straits, which therefore must have been open during the Main Monastirian also.

The Late Monastirian or 7·5 m. level is, apparently, less well preserved on the French coast. Some localities referred to the 18 m. level may belong to this stage. As a result of altimetric analysis Baulig (1935) found a distinct 8 m. level in the Pays de Léon (north-west Brittany).

FAUNA AND CLIMATE OF THE 18 M. TERRACE.—Under the influence of Depéret there has been a tendency to regard the phases of high sea-level as cold. Quite apart from other overwhelming evidence to the contrary, the mollusca which have been quoted in favour of a cold climate, especially during the Main Monastirian (18 m.) stage, are by no means conclusive. It is true that certain faunas show a tendency towards conditions slightly cooler than those of the present day (for instance, Portland, Baden-Powell, 1930), but generally the assemblages are temperate, with a small percentage of forms of chiefly northern range and others of chiefly southern range. This is to be expected, and does not prove a cold climate. Bigot (1930) revised some of the shell-faunas of north France, calling them "cool temperate, *not boreal*" (Bigot's italics). Even this is open to discussion. Above all, the *Buccinum grœnlandicum* from St. Aubin-sur-Mer, near Dieppe, has been recognized as a thin-shelled variety of the common whelk, *B. undatum*. Of the other "cool" species from this locality, *Bela turricula* and *B. trevelliana* do go far north in Europe, but they also occur on the coasts of Gascony, the extreme south-west of France. They can hardly be regarded as conclusive. *Chrysodomus antiquus*, reported by Dubois (1924), has not been found again. Dubois attributes St. Aubin to the regression from the Monastirian level after the beginning of the Last Glaciation.

Hue (1928) described a fauna from Luc-sur-Mer, near Caen, resting on bed-rock at 15 m. above sea-level, *i.e.* just below the Monastirian shoreline. This fauna includes *Bela turricula* and *Modiola modiolus* (see footnote below) as "northern elements," but on the other hand, there are *Rissoa proxima* and *Barleeia rubra*, two decidedly southern shells. One may interpret this combination as one likes, but one cannot say that this fauna proves cold conditions.

FLANDRIAN TRANSGRESSION.—Dubois, in his comprehensive monograph (1924), studied not only the high shore-lines of the Monastirian, but also the evidence for the phase of low sea-level following it, and the transgression leading up to the modern sea-level. After the Monastirian, the sea-level must have been at least 30 m. lower than to-day, while estuarine deposits, peats, etc., were formed. These are now much below sea-level. The transgression which submerged them is called the Flandrian. Halts or slight oscillations may have intervened, and it lasted into historic times. There are many reasons to suppose that the low sea-level preceding it was contemporary with the Last Glaciation. This Flandrian transgression has been established by Dubois in Flanders, the Calaisis, Picardy, Normandy, Brittany,

* *Modiola modiolus* occurs. This shell is now typically northern, but found on both coasts of the English Channel and reaches Loire Inférieure in the Gulf of Biscay. Here the species is smaller than in the north.

and on the Atlantic coast of the Armorican region. It is identical with the transgression observed by Blanc in the Lower Versilia (Italy, see p. 182), and partly with the Litorina transgression of the Baltic.

France : Summary.—Thus, the high shore-lines of north and west France agree closely with those of the Mediterranean. The earlier levels (103, 56–59, 32–33 m.) were correlated by Depéret with the Sicilian, Milazzian and Tyrrhenian respectively. They are rarely preserved, but at least the Tyrrhenian level passes through the Straits of Dover. The 18 m. or Main Monastirian shore-line with its temperate fauna is found almost everywhere. There is evidence for the post-Monastirian regression which laid the Straits of Dover dry, and for the following Flandrian transgression up to the present sea-level.

Rhine.—A short excursion east from the region of the English Channel takes us to the mouths of the Rhine. The terraces of this river form a complicated system which has been investigated locally in many places. Because of the complexity of the terrace-system of the lower Rhine and because of interference of tectonic movements in certain stretches, a synthesis has never been attempted. The terraces of the middle and upper Rhine are certainly due to climatic aggradation during glacial phases (p. 61). As they approached the sea, they must have increased their gradients to descend to the low sea-levels of the glacial phases. During the interglacials, erosion prevailed in the middle and upper course of the river, whilst the high sea-levels of these phases probably produced some aggradation in the lower part of the course. The obvious result of such interplay is a crossing of terraces, which has indeed been proved for two out of at least six terraces of post-Early Glaciation age (see Daly, 1934, fig. 100). It is unfortunate that the terraces of the Rhine have not yet been studied from the eustatic point of view.

Eem Sea.—In Holland and part of Belgium, north-west Germany, Denmark and north-east Germany as far as East Prussia, marine deposits are found between glacial beds. This " Eem " fauna is temperate and contains many " Lusitanian," *i.e.* south-western species. Its stratigraphical position has been under discussion for years. It has now found its place in the Last Interglacial (Nordmann, 1928). Thus, the Eem Sea is an equivalent of the Monastirian phase elsewhere, and its deposits are developed in that part of Europe where the submergence was shallow and cliffs were absent. The fauna affords an interesting parallel to the *Strombus*-fauna of the Mediterranean, though this alone would not decide its age, the *Strombus*-fauna having had a range greater than the Last Interglacial. The fauna of the Belle Hougue, Jersey, is probably exactly contemporaneous with the Eem phase ; whilst the slightly cooler faunas found in the Monastirian beaches in other places date perhaps from the beginning of the recession in the earliest stage of the Last Glaciation, or from some temporary, slightly cooler phase of the Last Interglacial.

Southern England.—In Chapter V it has been shown that the Pleistocene history of the Thames Basin suggests phases of high sea-level attaining to " 600 ft.," " 400 ft.," 200 ft., 100 ft., 60 ft., 25 ft. (and the interstadial level of a few feet above O.D.), the heights being increasingly more accurate as one approaches the Present. This sequence is so plainly the same as that of the Mediterranean, namely " Calabrian," " Sicilian," Milazzian,

Tyrrhenian, Main and Late Monastirian (plus the interstadial level not yet identified elsewhere), that the following summary of coastal evidence from southern England can be kept very short. It will receive fuller attention in another publication.

100 FT. LEVEL.—The Tyrrhenian (100 ft.) level is encountered for instance in the Portsmouth area, near Chichester (Palmer and Cooke, 1923 ; Fowler, 1932 ; Oakley and Curwen, 1937).

60 FT. LEVEL.—The Main Monastirian (60 ft.) level is found at Mousehole, near Penzance, west Cornwall (deposits to 65 ft. O.D., Dewey, 1935). Another deposit of this phase appears to be the Burtle Sands of Somerset (Bulleid and Jackson, 1937), which reach up to 50 feet O.D., contain a temperate shell fauna and an interglacial assemblage of mammals, including *D. dama*. A third deposit referable to the Main Monastirian is the fossil beach of Portland peninsula (Prestwich, 1875 ; Baden-Powell, 1930), which rests on a platform rising to 55 ft. O.D. Its shell fauna of 50 species contains a few forms tending towards northern varieties, together with *Gibbula umbilicata* (Montagu) and *Phasianella pulla* (L.) which are essentially southern.

An interesting deposit with a warm-temperate fauna is found at Selsey Bill, 15 miles east of Portsmouth (Godwin-Austen, 1857 ; Reid, 1892). Its shells point to a depth of 10 fathoms or more, and since the deposit is near low-water mark, one is tempted to refer it to the Main Monastirian level. Ten out of 38 species are southern. *Lutraria rugosa* and *Pecten polymorphus*, now Mediterranean and west African and not found north of Portugal, are noteworthy.

25 FT. LEVEL.—The Late Monastirian (25 ft.) sea-level is evidenced by numerous exposures* (commonly called "pre-glacial raised beach"). Its easternmost point is at Brighton, Sussex (White, 1924 ; Martin, 1929). Thence it can be followed westward to Devon where, at Torquay, it contains an interesting fauna (Hunt, 1888 ; Shannon, 1927 ; Ussher and Lloyd, 1933). In one locality (the Thatcher, Hunt, 1888), 43 species of marine mollusca were collected. Of these, *Trophon truncatus* and *Pleurotoma turricula* were regarded by Hunt as evidence of a rather cold temperature since, though they occur now in the Irish Sea, they are absent, or rare, on the south coast of England. On the other hand, *Pinna rudis*, *Adeorbis subcarinatus* and *Fusus jeffreysianus* are species of a predominately southern distribution.

In North Devon, Bideford or Barnstaple Bay affords interesting evidence for the 25 ft. shore-line (Pengelly, 1867). At Croyde, the fauna is considered as slightly warmer than the present (Baden-Powell, 1928). At Saunton, the beach deposits contain large blocks of erratics (Sedgwick and Murchison, 1837, 1840 ; M'Kenny Hughes, 1887), and are covered by fossil dune sands and by solifluction deposits. The erratics have been regarded as transported by floating ice, but the presence of genuine bottom moraine at Fremington suggests that they were derived from the moraine of a glacier which reached North Devon.

FREMINGTON BOULDER-CLAY.—There is unmistakable proof that the Pleistocene ice reached the north of Devonshire. At Fremington, south

* The sea-level of 30 ft. O.D. derived by J. F. N. Green (1943) chiefly from river profiles almost certainly belongs to this phase.

of the estuary of the Taw, in Bideford Bay, a brown clay is found which contains striated erratics, some apparently derived from Scotland. Dewey (1935) expressed the view that "it may be a true boulder-clay." Having visited the locality I cannot but emphatically support his suggestion. The clay is of a type known from at least three north German localities (Zeuner, 1928). In these the moraine is made up of brecciated clay derived from some pre-morainic deposit of ordinary homogeneous clay. It can be shown that the ice passed over a frozen deposit of clay, broke it up to form a breccia, and re-deposited it as bottom-moraine. The Fremington Clay is of this kind, and has to be regarded as the true bottom-moraine of an ice-sheet which, according to the incorporated erratics, came *via* the Irish Sea and the Bristol Channel rather than from Wales.

Since there is no evidence of ice transgression over the 25 ft. beach anywhere in Devon, the Fremington moraine must be older than this beach, and date from the Penultimate or some earlier glaciation.

In Wales and Ireland, however, the first phase of the Last Glaciation deposited moraine on the 25 ft. beach (p. 112).

Thus, the evidence for the fossil shore-lines of Atlantic Europe, outside the area dominated by isostatic readjustment in response to ice-cover, is in complete accord with the Mediterranean from the altimetric point of view. The marine fauna, well studied only for the two Monastirian phases, suggests a temperate climate much like the present one. In some localities slightly warmer conditions are indicated. The distribution of some species, however, differed from the present, some southern ones having penetrated farther north and east, some northern ones farther south, so that, by emphasizing the last-mentioned group, it is possible to suggest slightly cooler conditions. This can only be done by disregarding the warm component, however, and in any event the deviation from the present-day climate can only have been small. The climate of the Monastirian beaches therefore is best regarded as temperate, and interglacial. It certainly was not arctic, or glacial.

c. PLEISTOCENE SEA-LEVELS OUTSIDE EUROPE AND THE MEDITERRANEAN.

The preceding survey of some of the more important European localities which have afforded evidence for Pleistocene sea-levels has now to be supplemented by the review of a few regions outside Europe, in order to see whether the levels observed in Europe and the Mediterranean are universal or not.

Sunda Sea.—An interesting example of evidence for a very low sea-level of comparatively recent date is the Sunda Sea between Sumatra, Malakka and Borneo. Molengraaff (1921) studied the surrounding coasts and the topography and geology of the bottom of this sea. He found that the modern valleys continue beneath sea-level and form a complete submerged river-system, which opens into the China Sea between the islands of Great Natuna and South Natuna. The depth of the Channel at its mouth is about 100 m., and this figure must be near the actual amount of emergence during that phase. Later on Molengraaff (1930) and Umbgrove (1930) gave 70 m. and 90 m. respectively (see also Zeuner, 1943, p. 153), and Scrivenor, 1943, p. 122, who suggests 100 m).

It is doubtful whether the Sunda Sea can be called a submerged shelf in the sense of a marine platform of abrasion. From the published charts it appears to be an immersed or submerged river-system. In this and other respects it reminds one of the English Channel. The resemblance is increased by the presence of deposits of alluvial tin ore along the submerged river-courses in Cornwall and Sumatra respectively.

Scrivenor (1943, p. 122) found evidence for a sea-level of about + 50 ft. O.D. in Malaya, and less ambiguous evidence for one at + 200 ft.

South Africa.—The earliest description of "raised beaches" in South Africa is over a hundred years old (near Cape Town, Clarke, 1841). In 1871, Stow described further high-level beaches from the South African coast, and since then many papers have appeared dealing incidentally or exclusively with high marine levels, chiefly of the south coast of the Union. Krige (1927) studied and monographed them.

There is evidence for two groups of very high marine levels (240–300 m., and 135–165 m.), and a high one at 45–75 m. All three are in part covered by veneers of marine sediments of a Tertiary character, the faunas comprising a fair number of extinct forms (Haughton, 1925). In the two lower terraces (shore-lines at about 18 and 6 m., with a sub-stage of 4 m.) the fauna is modern, with very few extinct forms, but with many species which now are restricted to warmer waters (Rogers, 1905 ; Krige, 1927).

The relation of the higher terraces to the lower is thus surprisingly similar to that in the Mediterranean, at least for the last of the higher terraces and the two lower ones. The occurrence of a faunal break in areas so far distant from one another suggests that it is of major stratigraphical importance (see p. 232).

The exact heights of the ancient shore-lines are less easily determined in South Africa than on the European shores where very detailed maps are available. Tribute has to be paid to A. V. Krige for collecting a large number of measurements. In view of the difficulties and also of the fact that tectonic dislocations of the beaches have occurred in places, he considered as established only the levels enumerated above (and some higher ones which are of no import in this connection).

At Alexander Bay, near the mouth of the Orange River, however, Haughton (1932) found a succession of levels which resembles surprisingly that of Europe :

35–40 m. above sea-level. "Oyster Trench," Rock platform with fossiliferous deposits.

18–20 m. above sea-level. "Operculum Terrace." Well-developed planation with a few feet of fossiliferous gravel.

7·5 m. above sea-level. Lower shingle terraces, with 2 ft. 6 in. of gravel.

This locality substantiates the rather scanty evidence for the 32 m. level in South Africa.

The "20 ft. terrace" with its deposits exceeds this figure in a good many localities, as for instance at Mossel Bay, where, according to Goodwin and Malan (1935), the platform lies at 21 ft., with deposits up to 45 ft. Since the platform tends to drop away rapidly in the seaward direction on coasts with a heavy surf (Johnson, 1938, fig. 34), while storm beach deposits are piled up high above the actual level of the sea, this level can very well

be correlated with the 25 ft. shore-line of the Mediterranean and Atlantic Europe. Numerous caves are situated at 20–25 ft.; they would, in accordance with what has been said on p. 228, indicate the height of the sea-level more accurately than deposits.

A 60–70 ft. terrace also is very well marked. Its deposits appear to

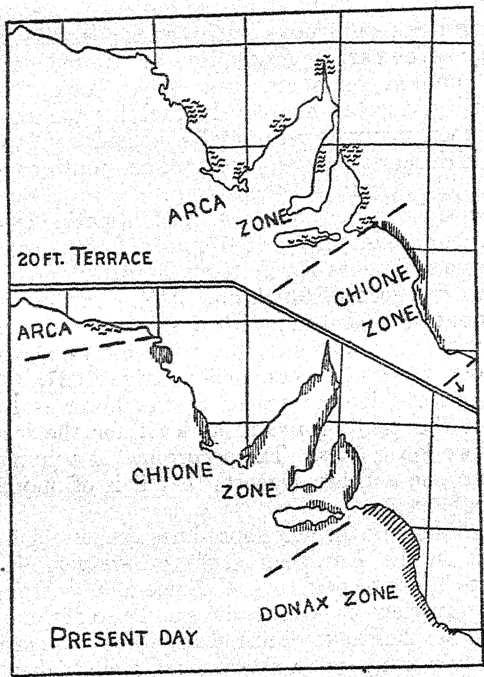


FIG. 75.—Zones of marine mollusca in the Australian Bight near Adelaide, South Australia. *Arca* is representative of a fauna requiring high temperature of the water, while *Donax* prefers comparatively cool conditions. *Chione* is intermediate.

Upper chart: Conditions during the 20 ft.-shoreline phase (Late Monastirian).

Lower chart: Present day. It is evident that the sea was warmer in Late Monastirian times. After Tindale, 1933.

reach about 75 ft. Again there are wave-cut caves; they suggest a shoreline of about 50–60 ft. Certain platforms, however, as that at Saldanha Bay (du Toit, 1917), lie as high as 60–70 ft. The heavy surf of this coast is perhaps responsible for the considerable variation.

Krige includes in his 60 ft. terrace points which possibly indicate one or two further, less distinctly preserved, levels. One might be at 45 ft. (about 8 localities out of 33 listed). This would agree with the highest terrace of the Eerste River as found by Shand (1914). Another level at about 100 ft., mentioned already from Alexander Bay, appears to be more distinct. It was observed by Schwarz (1906) at Cape Point, Van Rhyn's Dorp and

Strandfontein (conglomerates and sandstones, sometimes shelly, resting on platform). This level is confirmed by a cave at Cape Infanta at 100 ft., which Krige (1927, p. 30) definitely considers as carved by the sea. It contains a hardened beach-conglomerate.

Mention must further be made of the submerged Agulhas Bank, which lies south of Cape Agulhas, the southernmost point of Africa, extending a long way parallel to the coast. It is a typical continental shelf. It has been studied by Schwarz (1906) and du Toit (1922), who interpreted it as a beach platform cut when the sea-level was about 100 m. lower than at present, in consequence of glacial absorption of water. Krige (1927) discussed the evidence in detail. Rounded boulders are said to have been dredged from the Bank. Drowned valleys leading down to, and cut into, the shelf are observed. Krige, however, is inclined to explain the platform as scoured by submarine erosion, and claims to have evidence that the sea-level at some time was considerably lower than —100 m.

AUSTRALIA.—Less work than in South Africa has been done on ancient shore-lines in Australia, but the results are equally interesting. Howchin (1924) observed that on the south coast a young terrace contains shells indicative of a sea warmer than the present. The same was found by Clarke (1926) near Perth, Western Australia. Once more one is reminded of the warm Tyrrhenian fauna of the Mediterranean, of some of the Monastirian beach deposits of the Atlantic coasts of Europe, and of the low terraces of South Africa.

Tindale (1933) amplified these results, and compared the geographical arrangement of the shell faunas of the Great Australian Bight in the lowest, 25 ft., beach with those of the modern sea (Fig. 75). The figure shows how the faunal zones lay further south in 25 ft. shore-line times; the sea must have been warmer in those days.

In South-east South Australia Tindale distinguishes the following marine levels, 25 ft. (7·5 m.), 65 ft. (19·5 m.), 90 ft. (27 m.), 150 ft. (45 m.), 200 ft. (60 m.), 250 ft. (75 m.). Most of these levels are well known from other regions of the world. Only the 45 m. and 75 m. levels are rarely observed and therefore less certain. They are known from North America, and possibly South Africa and the Nile.

Tindale compared his shore-lines with those of the east coast of North America. The agreement is close indeed.

The Great Australian Bight contains a submarine shelf which slopes very gently down to about — 100 m., whence it drops rapidly to great depths.

EAST COAST OF NORTH AMERICA.—From Newfoundland down to Florida, marine terraces accompany the east coast of the North American continent. They have been studied by many workers, and are, from the physiographical standpoint, one of the best known series in the world. A summary has been published by Cooke (1930).

Since North America was glaciated as far south as New York, the possibility of isostatic displacement of terraces has to be taken into account. Fortunately about 1,000 miles of coast line are available south of the formerly glaciated area, and from New Jersey to Florida coastal terraces run largely parallel to the present sea-level. Six terraces have been distinguished which Cooke, mainly in accordance with earlier authors, describes as follows:

m.*	ft.	Marine terrace.	Glacial correlation. (Richards).	North American glacial chronology; Cooke's tentative correlation.
81	265	Brandywine	—	(Preglacial).
Low sea-level		—	—	(Nebraskan) Glacial.
65	215	Coharie	—	(Aftonian) Interglacial.
Low sea-level		—	—	(Kansan) Glacial.
49	160	Sunderland	—	(Yarmouth) Interglacial.
Low sea-level		—	—	(Illinoian) Glacial.
29	95	Wicomico	—	(Sangamon) Interglacial.
Low sea-level		—	—	(Iowan) Glacial.
20	65	Chowan	—	(Peorian) Interglacial.
Low sea-level		—	Illinoian (or Iowan)	(Early Wisconsin) (Glacial).
7·5	25	Pamlico	Sangamon (or Peorian)	(Mid Wisconsin).
Low sea-level		—	(? Iowan+) Wisconsin	(Late Wisconsin) (Glacial).
0	0	Recent	Recent	Recent.

Only in the 7·5 m. or 25 ft. terrace (Pamlico) have fossils been found so far. According to Richards (1936), the fauna everywhere bears out that the climate at the time when deposits where laid down on this terrace was warmer than at present.

Several North American authors have tried to fit some of the terraces into the Pleistocene chronology. Richards (1936) showed that the Pamlico terrace, though not more than a few metres above present sea-level, cannot be post-glacial. He considers it as Last Interglacial, but leaves it open whether this interglacial is represented by the Peorian or the Sangamon stage. In 1937 he was inclined to call it Sangamon. Cooke (1930), however, made an attempt to correlate all the known terraces with the interglacial phases of the North American chronology, on the (rather unfounded) assumption that no shore-lines have been overlooked and that none represent sub-stages. This correlation, which Cooke himself called highly speculative, is included in the table above. It is probable that Richards's view regarding the Pamlico as contemporary with the Sangamon (or Peorian) is correct.

South America.—The terraces of the South American west coast have received considerably more attention than those of the east coast. They are, however, known to have been raised to heights above their original position by the movements of the Andes and cannot, therefore, afford direct evidence for the height of the Pleistocene sea-levels. On the east coast the fossil beaches appear to be almost undisturbed over distances of hundreds of miles. This was established by Charles Darwin a hundred years ago (1846).

Darwin's numerous data, collected during the famous voyage of the "Beagle," are based partly on measurements, trigonometrical or barometrical, and partly on estimates in turn relying on measurements carried out in the neighbourhood. There is no reason to regard these figures as less reliable than those of later authors, though Darwin (in common with many later authors) gave the height of the levels often without specification as to which element of the fossil beach or platform they refer to. Whilst some of his figures are likely to be too low, being based on the submarine platform, others are probably too high, because of inclusion of covering strata of subaerial origin. In spite of these shortcomings Darwin's figures

are highly suggestive of a correlation of the South American beaches with those of the Mediterranean and other parts of the world.

In the following table Darwin's data are summarized.* A distinction is made between beaches with deposits containing marine shells, and those based on other evidence.

Locality.	Fossil beach. With shells.	Fossil beach. Without shells.
Bahia, 13° S. lat.	Lower than 20′	20′
Rio de Janeiro, 23° S.	15–20′	..
Montevideo, 35° S.	13–16′	..
Colonia del Sacramento, 35° S.	15′	..
San Pedro, Parana, 34° S.	100′	..
Buenos Aires (S. Isidro), 35° S.	40′	..
Punta Alta, Bahia Blanca, 39° S.	20′ above H.W.M.	..
Monte Hermoso, Bahia Blanca	..	120′
San Blas, mouth of R. Colorado, 40° 40′ S.	32′ (calc.)	15–20′
San José, 42° S.	80–100′	..
Bahia Nueva, 43° S.	..	80′ est.
Ditto	..	200–220′ meas.
Ditto	..	350′ meas.
Golfo de S. Jorge, 46° S.	..	250′ meas.
Ditto	..	350′ meas.
Capo de Tres Puntas, 47° S.	..	250′
Puerto Deseado, 48° S.	330′	100′
Ditto	250′	..
Opposite Bird Is., 49° S.	..	350′
Puerto S. Julian, 49° 30′ S.	90′ est	..
Sta. Cruz. 50° S.	..	355′
Coy Inlet, 51° S.	..	350′

This table contains all the localities for which Darwin has provided data. There are—

4 localities between 330 and 350 ft. (99–105 m.).
4 ,, ,, 200 ,, 250 ft. (60–75 m.).
5 ,, ,, 80 ,, 120 ft. (24–36 m.).
1 locality at 40 ft. (12 m.).
1 ,, at 32 ft. (9·6 m.).
6 localities between 15 and 20 ft. (4·5–6 m.).

The localities can thus be grouped as belonging to certain levels, all of which, except two, are evidenced by from 4 to 6 instances. Of the two "levels" represented by a single locality only, that of 32 ft. at San Blas was obtained by calculating the depth at which the contained fauna lived and is, therefore, worth little. The other one, 40 ft. at S. Isidro, I have been unable to check.

The four levels for which more ample evidence has been supplied by

* The temporary evacuation of large parts of the libraries has prevented me from obtaining data of more modern authors. Only the lower beach of Bahia Blanca has been checked on the Mapa geol.-econ. Rep. Argent., 1 : 200,000. The numerous papers by C. and F. Ameghino contain valuable material bearing on the fossil beaches of the Argentine.

After this chapter was written I was able to obtain Feruglio's paper (1933) on the coastal terraces of Patagonia. The absence of determinations of the mean sea-level makes it difficult to interpret his levels, though the Late (5–6 m.) and Main Monastirian (6–19 m.), Tyrrhenian (15–40 m.) and Milazzian (35–60 m.) appear to be present. Correlations with the Pampas Formation and the glaciations of the Andes are attempted.

Darwin agree surprisingly well with the levels observed in other parts of the world.

The fossil beaches of the east coast of South America are in stratigraphical contact with the Pampas Formation and often contain mammalian bones. The age of these important deposits is utterly uncertain, but it is to be hoped that, once the correlation of the coastal terraces of South America with the eustatic phases of the Pleistocene has been established, such deposits will provide the means for dating the Pleistocene divisions of the Pampas Formation as well as their fauna of extinct mammals.

As an instance, the 6 m. beach of Punta Alta near Bahia Blanca may be referred to, from which Darwin reports the following species (Owen's determination) : *Megatherium cuvieri* Desm., *Megalonyx jeffersoni* Leidy, *Mylodon darwinii* Owen, *Scelidotherium leptocephalum* Owen, *Toxodon* sp., *Equus curvidens* Owen, ? *Macrauchenia patachonica* Owen. If one is justified in correlating this beach with the late Monastirian, this wholly extinct fauna would have lived in late Pleistocene times (for age of the Late Monastirian level see p. 249).

6. THE WORLD-WIDE CHRONOLOGY OF SEA-LEVELS.

WORLD-WIDE OCCURRENCE OF CERTAIN ANCIENT SEA-LEVELS.—These remarks on South America conclude our sketchy survey of the evidence for Pleistocene sea-levels. It has abundantly shown that certain shore-lines at definite heights are of more than local interest, and that they occur again and again in widely distant regions (Zeuner, 1942). The only satisfactory explanation for this fact is eustasy.

The shore-lines suggested in this manner are best called by their Mediterranean names, or by the approximate height of mean sea-level. The following list summarizes the evidence :

Heights in metres.	Average height.	Algiers.	South France.	Jersey.	North France.	South Engl.	South Africa.	Sunda Archip.	South Austral.	North America.
Sicilian	100	103	90–100	..	103	c. 96	..	..		81
Milazzian	60	c. 60	55–60	..	56–59	c. 60	45–75	c. 60?	(75) 60 (45)	65 49
Tyrrhenian	32	c. 30	28–32	32–34	32–33	(36·5) 33·5	c. 32	..	27	29
Main Monastirian	18	18–20	18–20	18	18–19	15–18	18–20	c. 15	19·5	20
Late Monastirian	7·5	..	7–8	7·5	8	5–8	6–7·5	..	7·5	8
pre-Flandrian regression	–100	..	min. –92	..	min. –30	c.–100	–100	–70 to –100	–100	..

ALTERNATION OF HIGH AND LOW SEA-LEVELS.—The table comprises five high sea-levels and one low one. The latter (pre-Flandrian transgression) intervened (with oscillations, see p. 186) between the Late Monastirian sea-level of 7·5 m. O.D. and the modern one of zero O.D. Thus, it is

clear that a phase of lower sea-level separates at least these two phases of relatively high sea-level.

That the earlier phases of high sea-level also were separated by periods when the sea was low, is difficult to show on marine evidence, but the benches of the lower courses of the rivers show it very plainly. The periods of erosion in the lower Thames (p. 120) prove that, following the Milazzian, erosion cut down to a lower level during the Antepenultimate Glaciation, after which the sea rose again, and with it the lower part of the river, until the Tyrrhenian 32 m. level was attained. That, preceding the Main Monastirian, the sea was lower than at present is shown by the Taplow bench which plunges below zero O.D. in the Dartford area. Moreover, deep sunk channels continue many rivers in other parts of the world to far below present sea-level, to depths which cannot be ascribed to the pre-Flandrian transgression.

Thus we have to conclude that all high sea-level stages are separated from one another by phases of relatively lower sea-level. The ensuing sequence of oscillations is difficult to explain by any cause except fluctuations in the water volume of the oceans, as postulated by the theory of glacial eustasy.

Interglacial Age of High Shore-Lines.—The high shore-lines, therefore, should be interglacial. Though this view is now quite generally accepted, since faunal evidence, both terrestrial and marine, has provided ample confirmation, it is unfair to dismiss without explanation the arguments which have been brought forward in favour of the high shore-lines being contemporary with glacial phases. Evidence was supposed to exist (*a*) in the connection of high shore-lines with certain river terraces which, upstream in the mountains, were linked with moraines, and (*b*) in the cold elements of the shell fauna of some high beaches.

Point (*a*) is disproved by the fact that the moraines with their gravel trains have since been found to be superimposed on the terraces belonging to the high shore-lines.

Point (*b*), the palæontological argument, is interesting in several respects.

The Tyrrhenian and Late Monastirian beaches were, on the whole, warmer than the present sea (*Strombus*-fauna of the Mediterranean and its equivalents). The Main Monastirian level, however, is less consistent. There are localities with a warm fauna of the "Tyrrhenian" type, and others which contain some species now ranging further north. But it has been said above (p. 237) that these "cool" species are associated with "warm" ones which would readily cancel them out from the climatic standpoint and that, for this reason, the climate cannot have been very different from the present one. The same applies to the Sicilian fauna of the Mediterranean (p. 232) with *Cyprina islandica*. The case for this fauna is further weakened by its greater age, since it is a mistake to assume that the climatic requirements of species remain constant through long periods of time (Zeuner, 1936). It is evidently no longer admissible to regard the maximum shore-lines as contemporary with glacial phases.

On the other hand, it is quite conceivable that the presence of certain cool species indicates temporary slight reductions in the temperature of the sea, though it will be difficult to prove this. The argument of admixture put forward for the faunas of the English Crags (p. 105) applies here also.

Furthermore, deposits laid down during the beginning of a recession (*i.e.* at the beginning of a glacial phase) are very often referred to the preceding high sea-level, which is a conspicuous chronological landmark, while it is overlooked that the deposits covering a fossil abrasion platform date for the most part from the time of the final recession of the sea.

The interglacial character of the high shore-lines of the Pleistocene, therefore, can no longer be seriously challenged.

Glacial Age of Low Sea-Levels.—That the low sea-levels correspond to glacial phases is readily demonstrated for the last great drop, the pre-Flandrian regression, since the subsequent period of return to the present high sea-level has been proved contemporary with the return of the climate from glacial to the temperate one of the present day (the Flandrian transgression, Dubois, 1924). The -100 m. post-Monastirian sea-level thus appears to have coincided with the Last Glaciation.

This geological evidence tallies with the theory of glacial eustasy. A number of estimates have been made of the amount of water which was locked up in the ice-caps of the Last Glaciation, and the resulting drop in sea-level was calculated as—

75–85 m. by Daly (1934, p. 47).
83 m. by Antevs (1928, p. 81).
103 m. by Penck (1933).

The observed figures for the pre-Flandrian regression vary between 70 and 100 m.,* so that the agreement of deduction and observation is most satisfactory.

A third argument suggesting that the low sea-levels correspond to glacial phases can be based on the pre-Tyrrhenian faunal break (p. 233).

The Sequence of High Sea-Levels.—The curious feature of the sequence of Pleistocene high sea-levels is that each younger phase attained to a smaller maximum than the preceding.

One might be inclined to argue that a high sea-level destroys, or at least buries, the evidence for all preceding ones which were not so high, so that the step-like arrangement would ensue inevitably. There is, however, no evidence from sections which clearly corroborates this contention with regard to the major maxima, but it has to be kept in mind that certain, as yet unrecognized, smaller oscillations might have intervened in the sequence.

Now, if the altitudes reached by the sea in successive interglacials were solely due to deglaciation,† the latter being a function of the intensity of the interglacial climate, the interglacials should have been the warmer the greater their age. That this contradicts the available evidence is apparent from the regional surveys in Chapters II to IV. It must be assumed, therefore, that the eustatic oscillations of the sea-level are superimposed on a general, continuous depression of the sea-level due to other causes. This point has

* The figure of -30 m. obtained for the English Channel off the north coast of France is a minimum. It may be the correct figure for LGl_3. The maximum drop, however, was much greater, since the floor of the Channel slopes very gently to nearly -100 m. in a westward direction. To the west of Cornwall and Brittany, however, the gradient is much increased. A -100 m. level is thus indicated for the English Channel also.

† Complete deglaciation over the earth would raise the present sea-level by 40–50 m. only (Daly, 1934 p. 12); it could not therefore account for the Milazzian and Sicilian levels in any event.

been discussed before (p. 164); it is borne out in a most surprising manner by the application of the astronomical theory.

RELATIVE AGES OF THE HIGH SEA-LEVELS.—Before this can be shown it is necessary to restate the relative ages of the high sea-levels in a summarized form.

The two Monastirian beaches are both earlier than the Younger Loess (north France, Channel Islands). The Late Monastirian level was followed by the pre-Flandrian regression (water locked up by Last Glaciation), and the moraine of the first phase of the Last Glaciation rests on it in Ireland and Wales. It cannot, therefore, date from the interstadial $LGl_1/_2$, for which, moreover, another level, only a few feet above O.D., is suggested in the lower Thames (p. 134). That the Late Monastirian beach is Last Interglacial is thus apparent. The Main Monastirian beach has always been considered as almost contemporaneous with the Late one, and the two are regarded as a unit by many authors. It is likely, therefore, that the Main Monastirian also is Last Interglacial. That this level post-dates the Penultimate Glaciation is confirmed by the position of the corresponding river terrace relative to the Older Loess and contemporary solifluction phases in the Somme, and in the Thames.

The Tyrrhenian sea-level, therefore, may date from the Penultimate Interglacial, and the Milazzian from the Antepenultimate Interglacial. This is confirmed for the Milazzian for instance by the terrace of the Somme containing the *Machairodus*-fauna at Abbeville, which runs into this level (p. 89). Wooldridge has shown that the Milazzian level of the London Basin is later than the Norwich Crag (formed in Early Glaciation times), whilst the moraine which covers this platform is older than the Tyrrhenian 32 m. level (see p. 115). The Milazzian thus finds its place in the Antepenultimate Interglacial, which leaves the Great or Penultimate Interglacial for the Tyrrhenian sea-level.

ABSOLUTE CHRONOLOGY OF HIGH SEA-LEVELS.—With this knowledge of the relative age of the sea-levels a rough estimate of the absolute age of the interglacial sea-levels can be made by applying the radiation time-scale. Each maximum shore-line can, of course, have occurred at any time in the course of an interglacial. It is unlikely that the sea-level was stable throughout the interglacial, but when and for how long the maximum level was occupied is difficult to say. As to the Monastirian, it is reasonable to assume that the Main level was reached rather early during the Last Interglacial, since the Late Monastirian has to be accommodated in the later part of the same climatic phase. As to the Tyrrhenian, evidence from the lower Thames suggests that the 32 m. level was reached late during the Penultimate Interglacial.

Now, if one plots the heights of the present sea-level and of the Main Monastirian, Tyrrhenian and Milazzian shore-lines in relation to time and duration of the corresponding interglacials (Fig. 76), one finds that they can be connected by a straight line. Owing to the short duration of the Antepenultimate Interglacial but little play is available for this line. In our figure it is drawn on the assumption that the Milazzian maximum was attained late in the Antepenultimate Interglacial, but it is easy to see an earlier date for this maximum would displace the line but slightly. Quite apart from the line itself being an unexpected feature, it also complies with

the geological suggestions of a late date of the Tyrrhenian and an early date of the Main Monastirian sea-levels within their respective interglacials.

In my opinion, this coincidence renders it highly probable that the straight line represents the *continuous* drop of the sea-level during the Pleistocene, *i.e.* that part of the movement which is due to causes other than glacial eustasy (p. 225). It has amounted to about 70 m. in 600,000 years, or about one-tenth of a millimetre annually.

The Late Monastirian is the only beach which does not lie on our straight line. If geological dating is given priority, this means that deglaciation was slightly below the present-day amount ; had deglaciation been equal to that of the present day, this beach would be found at about 15 m. O.D. From this figure it is easy to calculate that in Late Monastirian times the

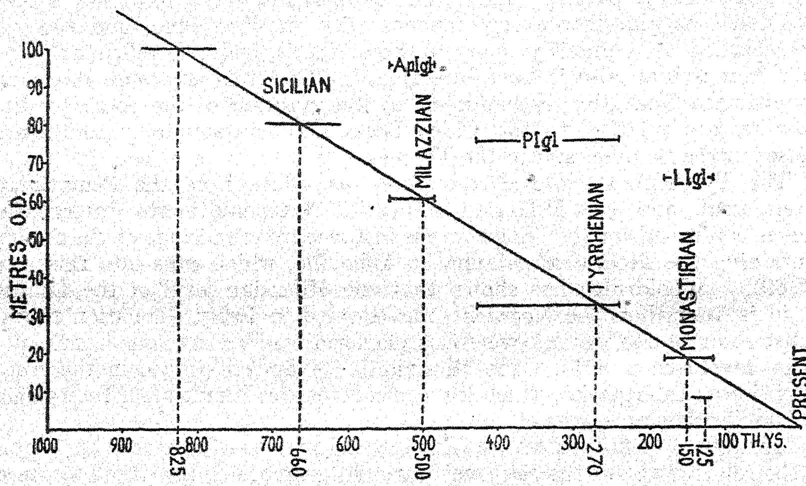


FIG. 76.—Diagram showing the relation of altitude to time for the high sea-levels of the Pleistocene. The horizontals representing the Main Monastirian, Tyrrhenian and Milazzian levels have the length of the corresponding interglacials on the time-scale.

amount of ice on the earth was only about one-sixth or one-seventh greater than to-day.

On the other hand, if one assumed that in Late Monastirian times deglaciation reached the same degree as to-day, this beach should have been formed at 65,000 B.P., a date which follows R.M. 72 of LGl_2 very closely. It is improbable that at that time interglacial conditions prevailed ; geological evidence points rather to the contrary. This alternative, therefore, has to be abandoned, and the Late Monastirian is best regarded as having occurred late in the Last Interglacial, somewhere about 125,000 B.P.

For the Main Monastirian, Tyrrhenian and Milazzian, approximate dates are provided by the points of crossing of our straight line with the horizontal, indicating the height of the beach. Thus, we obtain about 150,000, 270,000 and 500,000 B.P., respectively. It is preferable to use such " point dates " to indicate the approximate age of these beaches rather than the durations

of the interglacials. Everybody acquainted with their derivation will be aware of their tentative character.

If one continues the straight line beyond the Milazzian, one can arrive at a guess for the approximate age of the Sicilian. The Sicilian shoreline stood at one time at + 100 m., but in many parts of the world somewhat lower figures, between 80 and 100 m., are favoured. It is possible, therefore, that there were several Sicilian shorelines, the lowest being somewhere near 80 m. Both the 80 and 100 m. levels have been entered as limits in the graph, Fig. 76. They supply the very tentative date of between 660,000 and 825,000 B.P. for the Sicilian.* This corroborates the conclusion arrived at on geological grounds that the Sicilian immediately preceded the Early Glaciation.

Chronology of Low Sea-Levels.—Dates for the phases of low sea-levels are more easily obtained than for the high ones, since theoretically they should be contemporaneous with the glaciations. But geological evidence for low sea-levels is scanty and confined chiefly to that of the Last Glaciation. The section of the lower Versilia suggests that the pre-Flandrian low level of −100 m. belongs to the first phase of the Last Glaciation (p. 186). There is no conclusive evidence that the sea-level was less low during the two later phases of the Last Glaciation, but there are slight suggestions of a halt at −70 m. (Sunda Archipelago, Molengraaff, 1930) and at −30 m. or less (Dubois, 1924). It is conceivable that these are the low levels of LGl_2 and LGl_3.

The very low level of about −200 m., which has repeatedly been suggested, could not therefore be later than the Penultimate Glaciation. Since the latter was much more intense than the Last Glaciation, it is to be expected that more water was locked up in its ice-sheets, and that the sea-level was correspondingly below −100 m.

It may be pointed out that the sea-level diagram, Fig. 76, in conjunction with the estimates made for the ice-volumes of several glaciations, opens a way for the calculation of a new curve of the oscillations of the sea-level. Such curve would be considerably more reliable than that previously constructed on the basis of Soergel's glaciation curve (Zeuner, 1938).

It is desirable that more attention should be paid to the phases of low sea-level in general. It was during such phases that the land fauna was able to cross from continents to many outlying islands, and from continent to continent. There is a fair prospect of dating movements of this kind if the submarine shelves were studied in greater detail than hitherto and the results fitted into the absolute chronology of the Pleistocene.

Oscillation of R.M. 143.—Many other fascinating problems arise out of the correlation of the Pleistocene sea-levels with the absolute time-scale, such as the question of the oscillation between the two Monastirian levels which one is inclined, *prima facie*, to identify with R.M. 143 and possibly the Danish Middle Bed oscillation. In this kind of work, however, it will be necessary to avoid groundless speculation. Instead, the hints provided by the theory should be taken as an encouragement to intensify search for new geological evidence.

* Note that in Zeuner (1938) the Sicilian is erroneously placed in the Great Interglacial since, when that article was written, the author followed Blanc in regarding the Tyrrhenian as comprising the entire Monastirian.

SUMMARY AND CONCLUSION.—In this chapter an attempt has been made to cover some new ground, extending absolute dating to the coastal terraces of the continents. It has been shown that the four main shore-lines, the Milazzian (60 m.), Tyrrhenian (32 m.), Main Monastirian (18 m.) and Late Monastirian (7·5 m.) correspond to the three main interglacials. The following dates for high and low levels are suggested by the absolute chronology:

Phase.	Sea-level at—	Approximate date, years B.P.
Sicilian	+ 80–100 m.	660–825,000
Milazzian	+ 60 m.	500,000
Tyrrhenian	+ 32 m.	270,000
—	– 200 m. (?)	c. 235–188,000
Main Monastirian	+ 18 m.	150,000
Late Monastirian	+ 7·5 m.	125,000
pre-Flandrian	– 100 m.	115,000
Interstadial level slightly above O.D.	—	—
—	– 70 m. (?)	72,000
—	– 30 m. (?)	23,000

The reason why this line of research has been treated rather fully here is, perhaps, not obvious. It is not that the results obtained so far are spectacular, but the possibilities of finding new correlations and datings for fossiliferous and prehistoric deposits are great indeed.

If the absolute chronology of the Pleistocene is to be extended over the whole earth—and this must be our ultimate goal—the shore-lines will provide a most valuable guide. They are comparatively easy to study, much more so than the fluctuations of the land climate of a region, and finds of fossil fauna and early man will continue to be made on and in "raised beaches" or caves connected with ancient shore-lines. I am confident that this kind of work will play an increasingly important part in geochronology and, in the future, produce some of the much-needed long-distance correlations, as well as time-scales in years for regions in which the fluctuations of the land climate cannot be studied so readily as in Europe. In this way it should be possible eventually to fit our work on faunal and human evolution into a proper chronological frame.

Up to the present, however, the only region where the absolute chronology can be applied with profit to fossil faunas is Europe and the Mediterranean. The concluding chapter will deal with this most interesting matter.

CHAPTER X

FAUNAL EVOLUTION IN THE PLEISTOCENE

A. PLEISTOCENE CHRONOLOGY AND EVOLUTION.

APART from its obvious uses in stratigraphical geology, the chronology of the Pleistocene developed in the preceding chapters has its most important and promising field of application in biological evolution, in particular in the evolution of faunas and of phylogenetic lineages since the Tertiary. For the first time it is now possible to obtain an approximate idea of the rate of specific and subspecific evolutionary changes, measured in absolute time. A special, and yet exceedingly important, contribution can further be made by the new chronology of the Pleistocene to the evolution of the genus *Homo* and the development of human industries in relation to time and environment, but this subject is too vast to be discussed in the present context.*

This concluding chapter, therefore, is concerned with the evolution of the fauna in the course of the Pleistocene. There are two aspects of this matter. The first is that of the relation to time of the actual changes observable in phylogenetic lineages. The second is that of the changes in the composition of the faunas in the course of time. The latter aspect comprises changes in the area of distribution of the species, together with evolutionary changes which occurred in these species in the course of time. In spite of its greater complexity, this second, faunal, aspect is more easily studied, since the material which Nature places at our disposal is, in the first instance, faunal assemblages in dated deposits. It is only after a careful analysis of many such faunas that the phylogenetic lineages can be discerned in some of the species. The faunal aspect, therefore, is best considered first.

B. FAUNAL CHANGES IN THE LIGHT OF ABSOLUTE CHRONOLOGY.

Fossil land faunas from Pleistocene deposits are for the most part composed of mammalia and mollusca. As will be seen later on, the greatest changes are observed in the mammals, so that these have to be considered in more detail. In the following lists the mammals are given first, and the mollusca are thereafter summarized in tables.

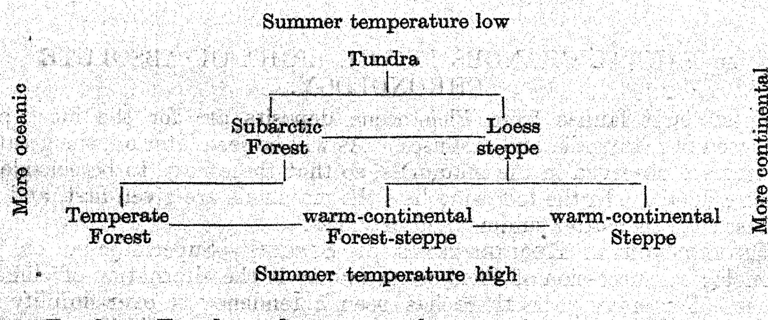
ENVIRONMENTAL REQUIREMENTS OF SPECIES.—Superimposed on the chronological succession of Pleistocene faunas is the alternation of climatic phases. For many years there has been a tendency to over-simplify the climatic character of the faunas, to classify them just as "cold" or "warm,"

* See Zeuner (1945).

and to interpret combinations of the two "types" as the result of later mixture of fossil remains. This view provides a relatively simple stratigraphical system, and is able to dispose of awkward species by considering them as derived. But it neglects the fact that in living faunas representatives of neighbouring biotopes mingle quite often, and that the environmental requirements of the species are rarely so restricted that they can exist only in a single specialized type of environment. The Musk-ox, for instance, is an exclusive denizen of the tundra to-day, but in Pleistocene times he lived on the loess-steppes also. The Reindeer has generally been taken as a tundra-dweller by palæontologists, but the various forest-forms, like the Caribou of Canada, show that this species does adapt itself to boreal forest (see Jakobi's reindeer monograph, 1931). On the other hand, the Lion used to be regarded as "warm," but has since proved to have been practically insensitive to temperature in the Pleistocene of Europe. The Mammoth is nearly always regarded as "cold," and *Elephas antiquus* as "warm." There is certainly some truth in this, but the primary adaptation of the former species was to open country, and of the latter to forest. If we recall how vast areas of the earth are covered with parklands or forest-steppes, it becomes clear that species of steppe and forest do mingle to a large extent. There is no objection to regarding these two elephants as contemporaneous in a locality, unless the preservation of the fossils proves derivation for one of the species.

Biotopes of Europe in the Pleistocene.—If these points are kept in mind fossil faunas reveal a much truer picture of conditions during the successive phases of the Pleistocene. One then begins to see, for instance, how an interglacial forest fauna gradually breaks up, how open-country forms join it, gain the ascendency, are reinforced by tundra elements, and how finally the forest forms disappear. Another interesting change is that from more oceanic to more continental conditions in the course of a glacial phase (p. 155): subarctic forest, and tundra, forms reigning during the earlier part, and steppe elements replacing them later on.

These changes are, of course, governed by the change of the environment, or biotope, which takes place in accordance with the fluctuations of the climate. The chief types of Pleistocene biotopes (exclusive of mountains) are the following (connecting lines indicating existence of transitions):



(1) *Tundra.*—Tree-less, dense ground vegetation, moist soil, often on tjæle. Regular snow-cover in winter. *Vulpes lagopus, Gulo gulo, Lepus*

timidus L. (varying hare), lemmings (esp. *Dicrostonyx*), *Tichorhinus antiquitatis*, *Rangifer tarandus* (tundra form), *Ovibos moschatus*, *Elephas primigenius*.

(2) *Subarctic Forest.*—(Including Taiga.) Coniferous forest, sometimes stunted or boggy, as now in northern Canada, Labrador, northern Russia and Siberia. Regular snow-cover in winter which enables this biotope to exist even in intensely continental climates. *Ursus arctos*, *Gulo gulo*, *Lynx lynx*, *Cervus elaphus*, *Alces alces*, *Rangifer tarandus* (forest form), *Bos primigenius*.

(3) *Temperate Forest.*—Deciduous forest. *Ursus arctos*, *Lynx lynx*, *Hippopotamus* (only where winters are mild), *Dicerorhinus merckii*, *Cervus elaphus*, *Alces alces*, *Bos primigenius*, *Bison* cf. *bonasus*, *Elephas antiquus*.

(4) *Warm-continental Forest-steppe.*—Parklands with deciduous woods interspersed with grasslands, as now found along the southern boundary of the forest towards the steppe in Russia and Siberia. Fauna a mixture of members of (3) and (5).

(5) *Warm-continental steppe.*—Grasslands with or without scrub, as now found in south Russia. Summers hot, snowy winters. *Lagomys* spp., *Alactaga jaculus*, *Citellus* spp., *Marmota bobac*, *Equus przewalskii* and other caballine horses, *Equus hemionus*, *Saiga tartarica*.

(6) *Loess-steppe.*—Treeless grasslands or scrub, less dense and lower growth than in (5), which catch and accumulate wind-blown dust. Climate cold, even in summer; winter with snow-cover; tjæle frequent. Not existing at present in Europe. Fauna as in (5), with the addition of *Vulpes lagopus*, *Lepus timidus* L. (varying hare), *Tichorhinus antiquitatis*, *Rangifer tarandus*, *Bison* cf. *priscus*, *Ovibos moschatus*, *Elephas primigenius*.

—. The following members of the Alpine fauna join those of (1) and (6) in the cold phases in the lowlands: *Marmota marmota*, *Capra ibex*, *Rupicapra rupicapra*.

—. The following have no particular preference for any of these biotopes: *Ursus spelæus*, *Felis leo spelæa*, *Hyæna* spp., *Megaceros* spp.

Development of Typical Faunas.—The lists of faunas which follow show that the environmental character is the clearer the younger the fauna. Generally speaking, faunas corresponding to the biotopes here distinguished are typically represented in the Upper Pleistocene only, whilst in the Middle Pleistocene the distinction is less complete, and almost non-existent in the Lower Pleistocene. This is to be expected if the differentiation of the faunas is the result of climatic fluctuations. The first few glacial phases are marked chiefly by the extinction of forms like *Machairodus*, *Leptobos* and several "Pliocene" deer which, apparently, were not sufficiently resistant to the new type of climate. But already some new-comers from the more continental east availed themselves of the opportunity to extend their area of distribution west- and south-westwards (*Trogontherium* in EGl, *Gulo*, *Tichorhinus*, *Rangifer*, *Ovibos* in ApGl, genera whose ancestors are unknown from the European Pliocene). By the second phase of the Antepenultimate Glaciation, these immigrants which were tolerant of a more continental climate had become numerous in species but not in individuals. Their appearance and the extinction of the "Pliocene" elements marks the establishment of the typical Pleistocene fauna in Europe.

It is characteristic of the immigrant elements of the Pleistocene fauna

that, at their first appearance, they are rare, and that they establish themselves only gradually, apparently as the result of the recurrence of suitable climatic phases. The reindeer, for instance, appeared in $ApGl_2$, but did not become frequent until LGl_1. This is a period of more than 300,000 years. Thus, hundreds of thousands of years and repeated phases of particularly suitable climate appear to have been necessary to establish these immigrants in Europe.* It is known that at least in some cases (*Ovibos* for instance) this process went hand in hand with morphological changes.

On the other hand, established members of the fauna responded readily even to slight climatic oscillations. A spreading of grassland at the expense of forest, as it accompanies a glacial phase, always causes the horses to increase in number, while red deer decrease. There are many other changes of this kind which show that the well-adapted members of biotopes (1) to (6) shifted their areas of distribution simultaneously with the biotopes, E.–W. or W.–E., and N.–S. or S.–N. These displacements must have occurred about ten times or more often during the Pleistocene, and since geological evidence suggests that the climatic changes were rapid, they must have been equally rapid, a matter of some 10,000 years. The mobility of mammals is certainly great enough, though for mollusca and plants one might consider such rapid shifts of whole environmental belts with their constituent faunas and floras over many degrees of latitude or longitude as improbable. Fortunately, the history of the Postglacial fauna and flora shows that 10,000 years did suffice to change the character of fauna and flora from glacial to interglacial. There are, of course, many lags. Of particular interest are those slow Postglacial migrants which, coming from the southeast, did not reach northern France before the English Channel was flooded, and thus were prevented from populating Britain. It is conceivable that, in the long run, a slow rate of migration resulted in elimination of species from the European fauna and flora. This is, perhaps, one reason why so many forms of life present in Europe in the Tertiary and now living in S.E. Asia and S.E. North America, and for which the European climate is suitable, are not found there under natural conditions.

Thus, two types of changes in the composition of Pleistocene faunas can be distinguished: a slow one due to the intrusion of new-comers, chiefly from the east (a matter of hundreds of thousands of years), and a rapid one due to wholesale shifting of faunas with their environments (a matter of about 10,000 years). The third change, due to phylogenetic evolution of the species composing the fauna, will be discussed after the faunal lists containing the evidence have been given.

* Hopwood (1938) considers that competition for food is the main obstacle for rapid establishment of new-comers. The establishment of the new-comer is of course a much more complicated process than shown in this context, but this interesting subject has no direct bearing on chronology.

c. THE SUCCESSION OF TERRESTRIAL FAUNAS IN THE PLEISTOCENE OF EUROPE.

MAMMALIA.

NOTE.

References.—Page of present work is given where locality is discussed in detail and where references to publications may be found. Further references in bibliography of present chapter.

Age.—For divisions of Pleistocene, see p. 175 (general), and p. 31 (detailed chronology). Dating either on geological evidence, or on palæontological grounds (*i.e.* considering phylogenetic stage of fauna relative to other geologically dated deposits). Age given in years B.P., neglecting retardation (see p. 168).

Fauna.—Classification following Miller's (1912) and Lydekker's (1887) catalogues. Question mark preceding name: horizon uncertain. Question mark following name: determination uncertain. For lists from some other localities, see Obermaier (1924).

VILLAFRANCHIAN.

The latest pre-Pleistocene faunas have an east Asiatic aspect (pig of *verrucosus*-group, tapir, etc.) and contain many essentially Neogene genera (*Mastodon, Machairodus*). Monkeys, a cheetah, horses of the zebra-group, tapir, *Leptobos* and several antelopes are prominent. *Mimomys pliocænicus* and *Elephas meridionalis* are characteristic of the late Villafranchian, but both continue into the earliest Pleistocene. The Villafranchian faunas are distinguished from slightly later ones chiefly by the absence of more advanced forms like *Elephas antiquus* and *Dicerorhinus merckii.*

LATE VILLAFRANCHIAN: VAL D'ARNO, TUSCANY, NORTHERN ITALY.

REF.—Major (1885), Weithofer (1890), Schaub (1928), Bernsen (1934).

AGE.—Determined palæontologically, contemporary with Senèze, slightly earlier than Tegelen. Immediately prior to Early Glaciation, *c.* 600 to 650,000 years B.P.

REMARKS.—List comprises both the lacustrine deposits of the upper Val d'Arno and the marine ones of the lower Val d'Arno. There is possibly an admixture of a somewhat earlier fauna, but this cannot be established with certainty.

FAUNA.—**Primates:** *Macacus florentinus* Cocchi (=*M. ausonius* Maj.). **Carnivora:** *Ursus etruscus* Cuv., *Canis etruscus* Maj., *C. majori* Del Camp., *C. olivolanus* Del Camp., *C. arnensis* Del Camp., *C. falconeri* Maj., *Vulpes alopecoides* Del Camp., *Proputorius nestii* Mart., *P. olivolanus* Mart., *Felis lunensis* Mart. (wild cat), *F. arvernensis* Cr. & Job. (*leo*-group), *Lynx issiodorensis* Cr. & Job., *Cynailurus elatus* (Brav.), *Machairodus cultridens* Cuv., *M.* sp., *M. meganthereon* Cr. & Job., *Hyæna perrieri* Cr. & Job. (=*H. robusta* Weith.=*H. brevirostris* Aym.?), *H. arvernensis* Cr. & Job. **Rodentia:** *Lepus valdarnensis* Weith., *L.* (*Oryctolagus*?) *etruscus* Bosco, *Hystrix etrusca* Bosco, *Mimomys pliocænicus* Maj., *M. newtoni* Maj., *Castor rosinæ* Maj., *C. plicidens* Maj. **Perissodactyla:** *Equus*

stenonis Cocchi (zebra-group), *E. stenonis major* Boule (=*E. robustus* Pom.), *E. quaggoides* Maj. (caballus-group), *E.* sp. (asinus-group), *Dicerorhinus etruscus* Falc. (type loc.), *D. leptorhinus* Cuv. (type loc.), *Tapirus arvernensis* Cr. & Job. **Artiodactyla:** *Sus strozzii* Men. (*S. verrucosus*-group), *Hippopotamus* sp., *Cervus dicranius* Nesti (=*C. sedgwicki* Falc.), *C. ctenoides* Nesti, *C. perrieri* Cr. & Job., *C. nestii* Maj., *C. etueriarium* Cr. & Job. (?), *Leptobos etruscus* Falc., *L. strozzii* (Rüt.) (female of *L. etruscus* ?), *Bubalus iselini* Stehl., *Nemorrhœdus meneghinii* (Rüt.), *Gazellospira torticornis* (Aym). (=*Palæoreas montiscaroli* Maj.), sp. cf. *Procamptoceras brivatense* Schaub, *Gazella* cf. *julieni* Mun.-Chal. **Proboscidea:** *Mastodon arvernensis* Cr. & Job., (?) *Mastodon borsoni* Hays., *Elephas meridionalis* Nesti.

LATE VILLAFRANCHIAN: SENÈZE, HAUTE LOIRE, FRANCE.

REF.—Stehlin (1923), Schaub (1928), numerous later papers in 'Ecl. geol. Helv.'

AGE.—Determined palæontologically. Immediately prior to Early Glaciation, *c.* 600 to 650,000 years B.P.

FAUNA.—**Primates:** *Macacus* sp., *Dolichopithecus* (? *Semnopithecus*) *arvernensis* Depéret. **Carnivora:** *Ursus etruscus* Cuv., *U. arvernensis* Cr. & Job., *Canis* cf. *arvernensis* Del Camp., *Vulpes megamastoides* Pom., *Felis* sp., *Machairodus cultridens* Cuv., *M. crenatidens* Fabr., *Ormenalurus* (?) sp., *Brachyprosopus vireti* Schaub, *Hyæna* cf. *perrieri* Cr. & Job., *H. arvernensis* Cr. & Job. **Rodentia:** *Oryctolagus* sp., *Mimomys pliocænicus* Maj., *M. newtoni* Maj., *M. pusillus* Méh., *M. intermedius* Newt. (teste Kormos), *Sciurus* sp. **Perissodactyla:** *Equus stenonis* Cocchi, *E. robustus* Pomel, *Dicerorhinus etruscus* Falc. **Artiodactyla:** *Sus* sp., *Cervus senezensis* Dep. (related to *C. teguliensis* Dub.), *C. philisi* Schaub (related to *C. rhenanus* Dub.), *Capreolus* sp. (?), *Leptobos etruscus* Falc., *Nemorrhœdus meneghinii* Rüt., *Procamptoceras brivatense* Schaub, *Gazellospira torticornis* (Aym.), *Deperetia ardea* (Dep.), *Megalovis latifrons* Schaub. **Proboscidea:** *Elephas meridionalis* Nesti.

LOWER PLEISTOCENE.

The passage from the Villafranchian to the Lower Pleistocene is almost imperceptible. The first phase of the Early Glaciation appears to have been a stimulus to the *Elephas meridionalis*-lineage, which produced the first *antiquus*-like molars, and the rhinoceros lineage of *Dicerorhinus etruscus* which evolved in the direction of *D. merckii*. *Trogontherium*, a beaver, is a new-comer, possibly from the east. The second phase of the Early Glaciation produced a *trogontherii*-like molar in some members of the *Elephas meridionalis*-group.

By the end of the Antepenultimate Interglacial, *Leptobos* and several of the "Pleistocene" deer had vanished from the scene. This interglacial is characterized by late *Elephas meridionalis*, *Machairodus*, *Dicerorhinus etruscus*, together with *Cervus elaphus*, *Alces*, *Dama savini* and *somonensis*, *Capreolus*, etc.

The oncoming Antepenultimate Glaciation is indicated by two arrivals from the north-east, *Ovibos* and *Gulo*. In the interstadial of the Antepenultimate Glaciation, the last *Machairodus* and *Trogontherium* are found,

but *E. meridionalis* has disappeared. The voles of the *Mimomys*-group have lost the roots of their molars and thus changed into *Arvicola* (Hinton, 1926*a*). *Homo* is found for the first time in a geologically dated deposit (*H. heidelbergensis*), though *H.* (*Eoanthropus*) *dawsoni* Smith Woodward from Piltdown is, on palæontological evidence, perhaps slightly older (Hopwood, 1935).

The second phase of the Antepenultimate Glaciation was the first intense glacial period. With it, the reindeer appears and the zebrine horses of Europe die out, whilst many forms which were still sufficiently like Villafranchian and ApIgl forms to be called by the same subspecific name, attain to a higher phylogenetic stage in the following phase (*Ursus deningeri*, *Hyæna brevirostris*, *Dicerorhinus etruscus*, *Megaceros verticornis*).

INTERSTADIAL $EGl_{1/2}$: TEGELEN, LIMBURG PROV., HOLLAND.

REF.—Bernsen (1934), Tesch (1934), Schreuder (1935, 1936).

AGE.—Determined geologically and palæontologically. Contemporary with Norwich Crag. *c.* 570,000 years B.P.

REMARKS.—First appearance of the *merckii*-type of rhinoceros, and of *Trogontherium*, latest of *Mimomys pliocænicus*.

FAUNA.—**Primates :** *Macacus* cf. *florentinus* Cocchi. **Insectivora :** *Desmana* sp. **Carnivora :** *Ursus etruscus* Cuv., *Pannonictis pliocænica* Korm., *P. pilgrimi* Korm. (=*Mustela* sp.), *Hyæna perrieri* Cr. & Job. **Rodentia :** *Hypolagus brachygnathus* Korm., *Hystrix* cf. *etrusca* Bosco, *Mimomys pliocænicus* Maj., *M. newtoni* Maj., *Trogontherium cuvieri* auctt. (=*Conodontes boisviletti* Laugel teste Schreuder), *Castor fiber* L. **Perissodactyla :** *Equus robustus* Pom., *Dicerorhinus etruscus* Falc., *D. merckii* Jäger. **Artiodactyla :** *Sus strozzii* Men., *Cervus dicranius* Nesti, *C.* cf. *ctenoides* Nesti, *C. teguliensis* Dub., *C. rhenanus* Dub., *Leptobos* cf. *etruscus* Falc.

INTERSTADIAL $EGl_{1/2}$: NORWICH CRAG, NORFOLK, ENGLAND.

REF.—Newton (1882), Reid (1890), Osborn (1922). See p. 104.

AGE.—Determined geologically. *c.* 570,000 years B.P.

REMARKS.—Determinations of fauna mostly dating from last century ; few revised. First appearance of elephants with molars resembling *E. antiquus*, latest of *Mimomys pliocænicus* and of *Mastodon arvernensis*.

FAUNA.—**Carnivora :** *Lutra* cf. *lutra* L., *L. reevei* Newt. (allied to *L. sivalensis* Falc. & Cautl.), *Machairodus* ? sp. **Rodentia :** *Mimomys pliocænicus* Maj. (=*Arvicola intermedius* Newt. partim), (?) *M. newtoni* Maj., *Trogontherium cuvieri* Fisch., *T. minus* Newt. **Perissodactyla :** *Equus robustus* Pom., *E. caballus fossilis* Rüt. **Artiodactyla :** *Cervus ardeus* Cr. & Job., *C. carnutorum* Laug., *C. falconeri* Dawk., *C. suttonensis* Dawk., *C. sedgwicki* Falc., *Gazella anglica* Newt., *G. daviesii* Hinton. **Proboscidea :** *Mastodon arvernensis* Cr. & Job., *Elephas* cf. *planifrons* Falc. & Cautl., *E. meridionalis* Nesti, *E.* cf. *antiquus* Falc. (doubtful, see Reid, 1890, p. 119).

ANTEPENULTIMATE INTERGLACIAL : ABBEVILLE, SOMME, NORTH FRANCE.

REF.—See p. 89. Fauna determined by M. Boule, see Commont, 1910, p. 259, with additions by d'Ault du Mesnil according to Breuil, and by Pontier (1910, 1928), who considers *Dicerorhinus leptorhinus* as identical with Merck's rhinoceros.

AGE.—Determined geologically, aggradation to Milazzian sea-level. *c.* 490,000 years B.P.

REMARKS.—First datable appearance of *Elephas* cf. *trogontherii*, latest of *Leptobos* cf. *etruscus*.

FAUNA.—**Carnivora:** *Ursus* sp. (small), *Mustela* cf. *nivalis* L., *Machairodus latidens* Owen, *Hyæna* (cf. *brevirostris* Aym.?). **Rodentia:** *Lepus* sp., *Trogontherium* sp. **Perissodactyla:** *Hippopotamus* sp., *Equus stenonis* Cocchi, *Dicerorhinus etruscus* Falc., *D. merckii* Jäg. (=*leptorhinus* Cuv.). **Artiodactyla:** *Cervus elaphus* L., *C. solilhacus* Rob., *Dama somonensis* Desm., *Megaceros belgrandi* Pohl., *Capreolus* sp., *Leptobos* cf. *etruscus* Falc. **Proboscidea:** *Elephas meridionalis* Nesti, *E.* cf. *trogontherii* Pohl. (primitive form), *E.* cf. *antiquus* Falc. (primitive form).

ANTEPENULTIMATE INTERGLACIAL: CROMER FOREST BED, NORFOLK, ENGLAND.

REF.—Newton (1882), Reid (1890), Sainty (1929), Osborn (1922), Zeuner (1937). See p. 105.

AGE.—Determined geologically and palæontologically. Possibly from the time of sinking sea-level previous to $ApGl_1$. *c.* 485,000 years B.P.

REMARKS.—Lower, Middle and Upper Freshwater Beds of West Runton and Cromer. Bacton, Trimingham and Mundesley excluded.

First appearance of *Elephas* cf. *primigenius*, *Bison*; last occurrence of *Cervus etueriarium*, *tetraceros*, *polignacus*, etc. *Mimomys* still typical; no *Arvicola* yet.

FAUNA.—**Primates:** *Macacus* sp. **Insectivora:** *Talpa* cf. *europæa* L., *Desmana magna* Owen (=*Myogale moschata* auctt.), *Sorex savini* Hinton, *S. runtonensis* Hinton, *Neomys newtoni* Hint., *Erinaceus* sp. n. **Carnivora:** *Ursus savini* Andr. (related to *U. deningeri*), *U.* cf. *spelæus* Ros., *U.* sp. (*arvernensis* Cr. & Job.?), *U.* cf. *ferox* Rich., *Canis* cf. *lupus* L., *C.* sp., *Vulpes* sp., *Lutra* sp., *Martes* cf. *martes* L., *Mustela nivalis* L., *Pannonictis* sp., *Felis leo spelæa* Goldf., *Machairodus* sp., *Hyæna* cf. *brevirostris* Aym., *H. hyæna* cf. *intermedia* Serres. **Rodentia:** *Lepus* sp., *Cricetus cricetus runtonensis* Hint., *Evotomys* cf. *glareolus* Schreb., *Microtus arvalinus* Hinton, *M. nivaloides* Maj., *M. nivalinus* Hint., *M. ratticepoides* Hint., *Pitymys gregaloides* Hint., *P. arvaloides* Hint., *Mimomys intermedius* Newt., *M. newtoni* Maj., *M. savini* Hint., *M. majori* Hint., *Apodemus* cf. *sylvaticus* L., *Sciurus vulgaris* L. (?), *S. whitei* Hint., *Trogontherium cuvieri* Fisch. (=*Conodontes boisviletti* Laug., teste Schreuder), *Castor fiber* L., *C. plicidens* Maj. (=*C. fiber* L. teste Schreuder). **Perissodactyla:** *Equus* cf. *robustus* Pom. (late form), *E.* cf. *mosbachensis* (caballine group), *Dicerorhinus etruscus* Falc., *D.* cf. *merckii* Jäg. (=*megarhinus* Christ.). **Artiodactyla:** *Sus* sp. n., *Hippopotamus* sp., *Cervus elaphus* L., *C. etueriarium* Cr. & Job. (?) (=*C. rhenanus* Dub., teste Bernsen), *C. tetraceros* Dawk., *C. sedgwicki* Falc., *C. polignacus* Rob., *Dama savini* Dawk., *Capreolus capreolus* L., *C. rectus* Newt., *Alces latifrons* Johns., *Megaceros verticornis* Dawk., *M. fitchii* Gunn (=*C. dawkinsi* Newt.?), *Bison* cf. *bonasus* L., *Ovis* (*Caprovis*) *savini* Newt. **Proboscidea:** *Elephas meridionalis cromerensis* Dép. & May.*, *E.* cf. *antiquus* Falc., *E.* cf. *trogontherii* Pohl., *E.* cf. *primigenius* Blum.

* ? Syn. of *E. meridionalis nesti* Pohlig.

ANTEPENULTIMATE GLACIATION, PHASE 1: BACTON FOREST BED, NORFOLK, ENGLAND.

REF.—Newton (1882), Reid (1890), Osborn (1922), Hinton (1926*a*, p. 391), Zeuner (1937). See p. 105.

AGE.—Determined palæontologically. *c.* 475,000 years B.P.

REMARKS.—Mostly last-century determinations. *Arvicola* replaces *Mimomys*. *Elephas meridionalis* derived? Some indication of cool conditions (*Ovibos*, *Gulo*), though *Hippopotamus* present according to Newton. Localities included: Bacton, Trimingham and Mundesley.

FAUNA.—**Insectivora:** *Talpa europæa* L. (?), *Myogale moschata* auctt. (?=*Desmana magna* Owen), *Sorex savini* Hint., *S. runtonensis* Hint. **Carnivora:** *Ursus* cf. *spelæus* Ros., *U.* "*ferox fossilis*," *Canis* sp., *Gulo* cf. *schlosseri* Korm., *Hyæna hyæna antiqua* Lank. **Rodentia:** *Arvicola bactonensis* Hint., *A. greeni* Hint., *Sciurus* sp., *Trogontherium cuvieri* Fisch. (?=*Conodontes boisviletti* Laug.). **Perissodactyla:** *Dicerorhinus etruscus* Falc. **Artiodactyla:** *Hippopotamus* sp., *Cervus elaphus* L., *C. sedgwicki* Falc., *C. polignacus* Rob., *Dama savini* Dawk., *Megaceros fitchi* Gunn (?=*C. dawkinsi* Newt.), *Bos* (s.l.) sp., *Ovibos* sp. **Proboscidea:** *Elephas meridionalis* Nesti, *E.* cf. *primigenius* Blum.

INTERSTADIAL $ApGL_1/_2$: MAUER, NEAR HEIDELBERG, WEST GERMANY.

REF.—Rüger (1931), Soergel (1933), Zeuner (1937). See p. 70.

AGE.—Determined geologically, confirmed palæontologically. *Arvicola* replacing *Mimomys*. *E. meridionalis* absent. c. 450,000 years.

REMARKS.—Contemporaneous with part of Mosbach fauna (Soergel, 1914; Zeuner, 1937), near Mainz. Mosbach, however, contains an earlier, and possibly also a later, component apart from the equivalent of the Mauer horizon. At Mosbach, *Dic. merckii* and *Megaceros verticornis* are found. The Mauer fauna here listed is that of the "Grafenrain" pit only. *E. trogontherii* probably comes from another pit, according to Soergel (1933).

Latest occurrence of *Machairodus*, *Lynx issiodorensis*, of *Hippopotamus* in the Rhine area, and probably of *Trogontherium*. All "Pliocene" types of deer have disappeared.

FAUNA.—**Primates:** *Homo heidelbergensis* Schoet. **Carnivora:** *Ursus deningeri* v. Reich., *U. arvernensis* Cr. & Job., *Canis mosbachensis* Soerg., *Felis catus* L., *F. leo spelæa* Golf., *F. pardus* L., *Lynx issiodorensis* Cr. & Job., *Machairodus* cf. *latidens* Owen, *Hyæna arvernensis* Cr. & Job. (= *mosbachensis* Geib.?). **Rodentia:** *Arvicola greeni* Hint., *Castor fiber* L., *Trogontherium cuvieri* Fisch. **Perissodactyla:** (?) *Equus stenonis* Cocchi (zebra-group), *E. mosbachensis* v. Reich. (caballus-group), *Dicerorhinus etruscus* Falc. **Artiodactyla:** *Sus scrofa prisca* Serres, *Hippopotamus* sp., *Cervus elaphus* L., *Alces latifrons* Johns., *Capreolus capreolus* L., *Bison priscus* Boj. **Proboscidea:** *Elephas antiquus* Falc. (primitive), (?) *E. trogontherii* Pohl.

ANTEPENULTIMATE GLACIATION, PHASE 2 (EARLY): SÜSSENBORN, NEAR WEIMAR, THURINGIA, CENTRAL GERMANY.

REF.—Soergel (1914, p. 221; 1924, etc.), Zeuner (1937).

AGE.—Determined geologically, climatic aggradation ending with Elster Glaciation. *c.* 440,000 years B.P.

REMARKS.—First appearance of *Rangifer*. *E. trogontherii* only. Latest occurrence of zebrine horses in Europe, of *D. etruscus*, *Leptobos* (?), etc. At Frankenhausen, Thuringia, *Tichorhinus antiquitatis* appears at this stage.

FAUNA.—**Insectivora:** *Talpa* sp. **Carnivora:** *Ursus süssenbornensis* Soerg. (*deningeri*-group), *Canis* cf. *mosbachensis* Soerg., *Meles* sp. (?), *Lutra* sp., *Hyæna brevirostris* Aym., *H.* cf. *crocuta* Erxl. **Rodentia:** *Myoxus glis* L., "Arvicolidæ," *Citellus* sp. **Perissodactyla:** *Equus* cf. *stenonis* Cocchi (?=*E. süssenbornensis*), *E. süssenbornensis* Wüst (latest of zebra-group), *E. germanicus* Nehr. (primitive, caballus-group), *Dicerorhinus etruscus* Falc. *D. hemitoechus* Falc. **Artiodactyla:** *Cervus elaphus* L., *C.* cf. *maral* Ogilby, *Alces latifrons* Johns., *Megaceros* cf. *verticornis* Dawk., *Capreolus capreolus* L., *Rangifer tarandus* L., *Leptobos* sp. (?), *Bison priscus* Boj., *Ovibos* sp. **Proboscidea:** *Elephas trogontherii* Pohl.

MIDDLE PLEISTOCENE.

The Middle Pleistocene fauna is characterized mainly by the absence of the interesting archaic forms of the Lower Pleistocene, and by the relative scarcity of the tundra and loess-steppe components which are so abundant in the cold phases of the Upper Pleistocene. Consequently, it has received less attention.

In the Penultimate or Great Interglacial we still find a monkey in temperate Europe. The characteristic elephant is *E. antiquus*, but specimens resembling *E. trogontherii* occur, though rarely, in deposits of a temperate character, the separation of the forest and steppe forms still being incomplete. A similar split into two ecological forms appears to have occurred in *Dicerorhinus*, with *D. merckii* as the forest and parkland form, and *D. hemitoechus* as a grassland form. *Dama clactonianus* is characteristic of the Great Interglacial. The Penultimate Glaciation has up to the present provided but poor faunas. These, however, indicate cold conditions and dominance of open country, with *Rangifer*, *Ovibos*, and *Tichorhinus*. The elephant of this phase is an advanced *E. trogontherii*, some molars having reached the *primigenius*-stage. *E. antiquus* withdrew from temperate Europe during the Saale Glaciation.

PENULTIMATE INTERGLACIAL: TRAVERTINE OF CANNSTATT, NEAR STUTTGART, SOUTH-WEST GERMANY.

REF.—Soergel (1929). See p. 72.

AGE.—Determined geologically. *c.* 340,000 years B.P.

REMARKS.—Fauna of middle travertine of Münster only. Other travertines of different age.

FAUNA.—**Carnivora:** *Ursus* cf. *arctos* L., *U.* cf. *spelæus* Ros. (primitive). **Perissodactyla:** *Equus* cf. *taubachensis* Freud., *Dicerorhinus* cf. *merckii* Jäg. (primitive), *D. hemitoechus* Falc. (teste Freudenberg). **Artiodactyla:** *Cervus elaphus* L., Bovinæ, sp. **Proboscidea:** *Elephas antiquus* Falc.

PENULTIMATE INTERGLACIAL: GRAYS THURROCK, ESSEX, ENGLAND.

REF.—Hinton (1926*a*, *b*), King and Oakley (1936). See p. 123.

AGE.—Determined geologically. Between 400 and 280,000 years B.P.

REMARKS.—Though age somewhat uncertain, a typical Great Interglacial fauna with *Dama clactonianus*, *Dicerorhinus merckii* and *hemitoechus*, and *Elephas antiquus*, plus a few *E. trogontherii*. A purely " Pleistocene " fauna, all Pliocene survivals having disappeared.

FAUNA.—**Primates:** *Macacus pliocœnica* Owen. **Insectivora:** *Neomys browni* Hint., *Sorex* sp. **Carnivora:** *Ursus* spp., *Vulpes vulpes* L., *Felis* cf. *catus* L., *Felis leo spelæa* Goldf., *Hyæna crocuta spelæa* Goldf. **Rodentia:** *Evotomys* cf. *glareolus* Schreb., *Microtus agrestoides* Hint., *Arvicola præceptor* Hint., *Castor fiber* L. **Perissodactyla:** *Equus caballus mosbachensis* v. Reich., *Dicerorhinus merckii* Jäg. (=*Rhinoceros megarhinus* auctt.), *D. hemitoechus* Falc. **Artiodactyla:** *Sus* cf. *scrofa* L. (large form), *Hippopotamus* sp., *Cervus elaphus* L., *Dama clactonianus* Falc., *Megaceros* sp., *Capreolus* sp., *Bos* sp., *Bison* sp. **Proboscidea:** *Elephas antiquus* Falc., *E. trogontherii* Pohl. (rare).

PENULTIMATE INTERGLACIAL: CLACTON-ON-SEA, ESSEX, ENGLAND.

REF.—Warren (1923), Oakley and Leakey (1937). See p. 123.

AGE.—Determined palæontologically. Between 400 and 280,000 years B.P.

REMARKS.—See Grays Thurrock.

FAUNA.—**Carnivora:** *Ursus* sp., *Felis leo spelæa* Goldf., *Hyæna* sp. (?). **Rodentia:** *Microtus* cf. *agrestoides* Hint., *Arvicola* sp., *Castor fiber* L. **Perissodactyla:** *Equus caballus mosbachensis* v. Reich., *Dicerorhinus merckii* Jäg., *D. hemitœchus* Falc. **Artiodactyla:** *Sus* cf. *scrofa* L., *Hippopotamus* sp. (?), *Cervus elaphus* L., *Dama clactonianus* Falc. (=*C. browni* Dawk.), *Megaceros* sp., *Bos primigenius* Boj., *Bos* sp. (small), *Bison priscus* Boj., *Capra* sp. **Proboscidea:** *Elephas antiquus* Falc.

PENULTIMATE INTERGLACIAL: LOWER GRAVEL, SWANSCOMBE, KENT, ENGLAND.

REF.—Swanscombe Report (1938). See p. 121.

AGE.—Approximately like Clacton and Grays.

REMARKS.—Only Barnfield Pit, Lower Gravel and Lower Loam; list kindly supplied by Mr. A. S. Kennard, A.L.S. Note that Ingress Vale near Greenhithe, Kent, which is often included in that of the Lower Gravel of Swanscombe, has yielded a fauna which is curiously reminiscent of Lower Pleistocene deposits. This has been emphasized repeatedly by Hinton (*e.g*, 1926*a*, p. 126). For list of Ingress Vale, see Stopes (1904). See p. 115.

FAUNA.—**Carnivora:** *Ursus* cf. *spelæus* Ros., *Canis* sp., *Felis leo spelæa* Goldf. **Rodentia:** Microtinæ indet. **Perissodactyla:** *Equus* cf. *caballus* L., *Dicerorhinus merckii* Jäg. **Artiodactyla:** *Cervus* cf. *elaphus* L. (small), *Dama clactonianus* Falc., *Bison* sp. **Proboscidea:** *Elephas antiquus* Falc., *E. trogontherii* Pohl.

PENULTIMATE INTERGLACIAL (LATE): MIDDLE GRAVEL, SWANSCOMBE, KENT, ENGLAND.

REF.—Swanscombe Report (1938). See p. 121.

AGE.—Just prior to Tyrrhenian high sea-level. *c.* 275,000 years B.P.

REMARKS.—Determined geologically. Lower Middle Gravel and *Homo*-horizon only; list kindly supplied by Mr. A. S. Kennard, A.L.S.

FAUNA.—**Primates:** *Homo* cf. *sapiens* L. **Perissodactyla:** *Equus* cf. *caballus* L. (*plicidens*-group teste Hopwood), *Dicerorhinus* sp. **Artiodactyla:** *Cervus* cf. *elaphus* L., *Dama clactonianus* Falc., *Bison* sp. **Proboscidea:** *Elephas antiquus* Falc., *E.* sp.

PENULTIMATE GLACIATION, PHASE 1 (EARLY): SECOND GLACIAL TERRACE, THURINGIA, CENTRAL GERMANY.

REF.—Toepfer (1933, 1934, 1935). See p. 56.

AGE.—Determined geologically. *c.* 235,000 years B.P.

REMARKS.—Localities Lengefeld (L) and Camburg (C) on the Saale.

FAUNA.—**Carnivora:** *Ursus* cf. *arctos* L. (L). **Rodentia:** *Castor fiber* L. (L). **Perissodactyla:** *Equus* cf. *germanicus* Nehr. (L), *Dicerorhinus merckii* Jäg. (L), *Tichorhinus antiquitatis* Blum. (L, C). **Artiodactyla:** Bovinæ indet. (L, C), *Capra ibex camburgensis* Toepf. (C). **Proboscidea:** *Elephas antiquus* Falc., tending towards *trogontherii* Pohl. teste Soergel.

PENULTIMATE GLACIATION, PHASE 2 (EARLY): RIVER TERRACES OF SAALE AREA, CENTRAL GERMANY.

REF.—Grahmann (1935), Lehmann (1922), Soergel (1924). See p. 57.

AGE.—Determined geologically; climatic aggradations just prior to arrival of Saale ice in the area. *c.* 190,000 years B.P.

REMARKS.—Localities Markkleeberg, near Leipzig (M), Körbisdorf on the Unstrut (K), Wettin on the Salzke (W), and river Ilm near Weimar (I). Fauna poor, but decidedly "cold." Elephants of *primigenius*-type beginning to replace *E. trogontherii*.

FAUNA.—**Perissodactyla:** *Equus caballus* L. (M), *Tichorhinus antiquitatis* Blum. (M, I). **Artiodactyla:** *Rangifer tarandus* L. (K), *Ovibos moschatus* Zimm. (W). **Proboscidea:** *Elephas trogontherii* Pohl. (M), *E. primigenius* Blum. (M, I).

UPPER PLEISTOCENE.

In the upper Pleistocene, faunas are climatically more clearly distinguished. Since the temperate-interglacial climate is more or less the continuation of the pre-Pleistocene climate, interglacial faunas are predominately composed of conservative forms such as brown bear, *Castor fiber*, *Hippopotamus*, red deer, etc. The elephant of the Last Interglacial is *E. antiquus* (late form). It did not survive this interglacial in temperate Europe.

The chief mark of the upper Pleistocene is the cold faunas of the three phases of the Last Glaciation. By this time, immigration and adaptive evolution had supplied a large number of species well fitted for the periglacial biotopes. Many, present in small numbers in earlier cold phases,

now become abundant; arctic fox, varying hare, lemmings and susliks (*Citellus*), caballine horses, woolly rhinoceros, reindeer, musk-ox, mammoth (*E. primigenius* s. str.).

A peculiar addition to the upper Pleistocene fauna is *Cuon alpinus* Pallas, a dog of a genus now restricted to eastern and central Asia as far south as Java.

LAST INTERGLACIAL: WILDKIRCHLI, SÄNTIS, SWITZERLAND.

REF.—Bächler (1906), Penck and Brückner (1908), Koken (1912).

AGE.—Determined geologically (Penck, 1908, p. 1174). Between 180 and 125,000 years B.P.

REMARKS.—A mountain cave, 1500 m. O.D.; good instance of an alpine interglacial fauna.

FAUNA.—**Carnivora:** *Ursus spelæus* Ros. (99 per cent. of bones), *Canis lupus* L., *Cuon alpinus* Pall., *Meles meles* L., *Lutra lutra* L.(?), *Martes martes* L., *Felis leo spelæa* Goldf., *Felis pardus* L. **Rodentia:** Arvicolidæ, *Marmota marmota* L. **Artiodactyla:** *Cervus elaphus* L., *Capra ibex* L., *Rupicapra rupicapra* L.

LAST INTERGLACIAL: BRUNDON, NEAR SUDBURY, SUFFOLK, ENGLAND.

REF.—Hopwood (1939).

AGE.—Determined geologically. Between 180 and 125,000 years B.P.

REMARKS.—An interglacial parklands fauna.

FAUNA.—**Carnivora:** *Ursus spelæus* Ros., *Canis lupus* L., *Felis leo spelæa* Goldf. **Perissodactyla:** *Equus caballus* L., Rhinocerotidæ sp. **Artiodactyla:** *Cervus elaphus* L., *Megaceros giganteus* Blum., *Bos primigenius* Boj., *Bison priscus* Boj. **Proboscidea:** *Elephas antiquus* Falc., *E. primigenius* Blum.

LAST INTERGLACIAL (LATE): LOWER TRAVERTINE OF EHRINGSDORF, NEAR WEIMAR, THURINGIA, CENTRAL GERMANY.

REF.—Soergel (1926), Koken (1912). See p. 67.

AGE.—Determined geologically, between R.M.143 and R.M.115. *c.* 130,000 years B.P.

REMARKS.—Late Last Interglacial, corresponding to Late Monastirian phase. Climate very mild, with *Thuja* and Walnut. A typical interglacial forest fauna.

FAUNA.—**Primates:** *Homo neanderthalensis* King. **Insectivora:** (?) *Sorex araneus* L. **Carnivora:** *Ursus* cf. *arctos* L., *U. spelæus* Ros., *Canis lupus* L., *C. suessi* Wold. (teste A. Weiss), *Vulpes vulpes* L., *Meles meles* L., *Lutra lutra* L., *Martes martes* L., *Felis catus* L., *F. leo spelæa* Goldf., *Lynx lynx* L., *Hyæna crocuta spelæa* Goldf. **Rodentia:** (?) *Lepus* sp., *Myoxus glis* L., *Cricetus cricetus* L., (?) *Arvicola amphibius* L., *Castor fiber* L. **Perissodactyla:** *Equus* cf. *abeli* Ant., *Dicerorhinus merckii* Jäg. **Artiodactyla:** *Sus scrofa antiqui* Pohl., *Cervus elaphus antiqui* Pohl., *Dama dama* L., *Alces alces* L., *Megaceros germanicus* Pohl., *Capreolus capreolus* L., *Bos primigenius* Boj., *Bison priscus* Boj., (?) *Capra* sp. **Proboscidea:** *Elephas antiquus* Falc.

LAST INTERGLACIAL (LATE): BRENTFORD, MIDDLESEX, ENGLAND.

REF.—See p. 126.

AGE.—Determined geologically. *c.* 130,000 years B.P.

REMARKS.—Fauna of new site on Great West Road; determinations kindly supplied by Dr. A. T. Hopwood. Interglacial forest fauna.

FAUNA.—**Carnivora:** *Hyæna* cf. *crocuta* Erxl. **Artiodactyla:** *Hippopotamus* sp., *Cervus elaphus* L., *Megaceros* sp., *Bos primigenius* Boj., *Bison priscus* Boj. **Proboscidea:** *Elephas antiquus* Falc.

LAST GLACIATION, PHASE 1 (EARLY): GROTTE DE COTENCHER, JURA MOUNTAINS, SWITZERLAND.

REF.—Dubois and Stehlin (1932, 1933).

AGE.—Determined geologically. *c.* 120,000 years B.P.

REMARKS.—Fauna a mixture of forest and alpine types enriched by some tundra and steppe forms. Climate becoming cold on approach of ice of LGl_1, but forests still persisting.

FAUNA.—**Insectivora:** *Sorex* sp. **Chiroptera:** *Rhinolophus ferrum-equinum* Schreb., *Myotis myotis* Borkh., *M.* sp., *Plecotus* cf. *auritus* L., *Miniopterus schreibersi* Kuhl. **Carnivora:** *Ursus arctos* L., *U. spelæus* Ros., *Canis lupus* L., *Cuon alpinus europæus* Bourg., *Vulpes vulpes* L., *V. lagopus* L., *V.* cf. *corsac* L., *Martes martes* L., *Mustela erminea* L., *M. nivalis* L., *Putorius putorius* L., *Gulo gulo* L., *Felis catus* L. (=*F. silvestris* Schreb.), *F. leo spelæa* Goldf., *F. pardus* L., *Lynx lynx* L., *L.* cf. *pardina* Temm. **Rodentia:** *Lepus timidus* L. (=*L. variabilis* Pall.), *Eliomys* cf. *quercinus* L., *Myoxus glis* L., *Cricetus cricetus* L., two other cricetids, *Dicrostonyx henseli* Hint., *Evotomys glareolus* Schreb., *Microtus nivalis* Mart., *M. ratticeps* Keys. & Blas., *M. anglicus* Hint., *M. arvalis* Pall., *Arvicola* cf. *amphibius* L., *Apodemus sylvaticus* L., *Sciurus vulgaris* L., *Marmota marmota* L. **Perissodactyla:** *Equus* cf. *taubachensis* Freud. or *abeli* Ant., *Dicerorhinus merckii* Jäg. (??), *Tichorhinus antiquitatis* Blum. **Artiodactyla:** *Sus scrofa* L., *Cervus elaphus* L., *Rangifer tarandus* L., Bovinæ indet., *Capra ibex* L., *Rupicapra rupicapra* L.

LAST GLACIATION, PHASE 1 (LATE): WALLERTHEIM, NEAR MAINZ, WEST GERMANY.

REF.—Schmidtgen and Wagner, see p. 67.

AGE.—Determined geologically. *c.* 110,000 years B.P.

REMARKS.—Swampy deposits of a watering place in the steppe at the end of the loess phase when climate was improving and forests spreading. Lions and bisons of extraordinary size.

FAUNA.—**Carnivora:** *Ursus spelæus* Ros., *Vulpes lagopus* L., *Felis leo spelæa* Goldf. **Rodentia:** *Arvicola* sp., *Marmota bobac* Müller. **Perissodactyla:** *Equus przewalskii* Pol. (=*E. ferus* Pall.), *E. germanicus* Nehr., *E. hemionus* Pall.(?), *Tichorhinus antiquitatis* Blum. **Artiodactyla:** *Sus scrofa* L., *Cervus elaphus* L., *Rangifer tarandus* L., *Bison* cf. *bonasus* L., *B. priscus* Boj. **Proboscidea:** *Elephas primigenius* Blum.

INTERSTADIAL $LGl_{1/2}$: UPPER TRAVERTINE OF EHRINGSDORF, NEAR WEIMAR, THURINGIA, CENTRAL GERMANY.

REF.—See Lower Travertine, p. 67.

AGE.—Determined geologically. *c.* 90–100,000 years B.P.

REMARKS.—Temperate fauna, with some steppe forms and one cool species (*Rangifer*) probably from the lower layers. Soergel maintains that three phases are represented, (1) temperate-continental, (2) cooler phase with steppe, (3) milder temperate phase.

FAUNA.—**Carnivora**: *Lutra lutra* L., *Putorius putorius* L., *P. eversmanni* Less. **Rodentia**: *Myoxus glis* L., *Cricetus cricetus* L., *Microtus arvalis* Pall. or *agrestis* L. **Perissodactyla**: *Equus* sp. (large), *E. hemionus* Pall. (very small, =*E.* (*Asinus*) *hydruntinus* Reg.?, teste Stehlin), *Dicerorhinus hemitœchus* Falc., *Tichorhinus antiquitatis* Blum. **Artiodactyla**: *Cervus elaphus* L. (large), *Megaceros* cf. *germanicus* Pohl., *Capreolus capreolus* L. (large eastern form), *Rangifer tarandus* L., *Bos primigenius* Boj., *Bison priscus* Boj. **Proboscidea**: *Elephas primigenius* Blum.

LAST GLACIATION, PHASE 2: YOUNGER LOESS AT THIEDE, NEAR BRUNSWICK, NORTH-WEST GERMANY.

REF.—Nehring, in Koken (1912, p. 217).

AGE.—Inferred on geological and palæontological grounds. *c.* 70,000 years B.P.

REMARKS.—Typical loess steppe.

FAUNA.—**Chiroptera**: *Plecotus auritus* L. (?), *Eptesicus nilssonii* Keys. & Blas. (?). **Carnivora**: *Canis lupus* L., *Vulpes vulpes* L., *V. lagopus* L., *Mustela erminea* L., *M. nivalis* L., *Putorius putorius* L., *Felis leo spelæa* Goldf., *Hyæna crocuta spelæa* Goldf. **Rodentia**: *Lepus timidus* L. (?), *Lagomys pusillus* Pall., *Alactaga jaculus* Pall., *Lemmus lemmus* L., *Dicrostonyx torquatus* Pall., *Microtus ratticeps* Keys. & Blas., *Pitymys gregalis* Pall., *Arvicola amphibius* L., *Citellus altaicus* Eversm. **Perissodactyla**: *Equus caballus* L., *Tichorhinus antiquitatis* Blum. **Artiodactyla**: *Megaceros giganteus* Blum., *Rangifer tarandus* L., Bovinæ indet., *Ovibos moschatus* Zimm. **Proboscidea**: *Elephas primigenius* Blum.

LAST GLACIATION, PHASE 2: YOUNGER LOESS OF MAINZ BASIN, WEST GERMANY.

REF.—Schmidtgen, see p. 66.

AGE.—Determined geologically. *c.* 70,000 years B.P.

REMARKS.—Typical loess steppe of Younger Loess II. All from Linsenberg except steppe marmot, from Wallertheim. Westernmost area reached by steppe marmot (see also LGl_1: Wallertheim).

FAUNA.—**Carnivora**: *Ursus spelæus* Ros. **Rodentia**: *Marmota bobac* Müller. **Perissodactyla**: *Equus przewalskii* Pol., *Tichorhinus antiquitatis* Blum. **Artiodactyla**: *Rangifer tarandus* L. **Proboscidea**: *Elephas primigenius* Blum.

LAST GLACIATION, PHASE 2 (LATE): KESSLERLOCH AND SCHWEIZERSBILD, NEAR SCHAFFHAUSEN, LAKE CONSTANCE AREA, SWITZERLAND.

REF.—Studer (1904), Heierli (1907), Nüesch (1896), Koken (1912). See p. 47.

Age.—Determined geologically. *c.* 65,000 years B.P.

Remarks.—Contemporary faunas of Kesslerloch and the "yellow culture stratum" of Schweizersbild. If found in one locality only, species marked (K) or (S).

Composite fauna of tundra and subarctic forest, with a few elements from the steppe and others from the Alps. Indicative of slightly less continental conditions prevailing after the climax of the glacial phase.

Fauna.—**Insectivora:** *Talpa europæa* L. (S), *Sorex araneus* L., *Crocidura russula* Herm. (=*C. araneus* Schreb.) (S). **Carnivora:** *Ursus arctos* L., *Canis lupus* L., *Vulpes vulpes* L., *V. lagopus* L., *Lutra lutra* L. (K), *Martes martes* L., *Mustela erminea* L. (S), *M. nivalis* L.(?) (S), *Gulo gulo* L., *Felis manul* Pall., *F. leo spelæa* Goldf. (K), *Lynx lynx* L. (K). **Rodentia:** *Lepus timidus* L. (??), *L. europæus* Pall. (K), *Lagomys pusillus* Pall. (S), (?) *Myoxus glis* L. (K), *Cricetus cricetus cricetus* L., *Dicrostonyx torquatus* Pall. (K), (?) *Microtus nivalis* Mart. (K), *M. arvalis* Pall. (S), *Arvicola terrestris* L. (K), *A. amphibius* L. (S), *Sciurus vulgaris* L. (S), (?) *Citellus guttatus* Pall. (K), *C. rufescens* Keys. & Blas., *Marmota marmota* L. (K), *Castor fiber* L. **Perissodactyla:** *Equus caballus przewalskii* Pol., *E. hemionus* Pall. (asinus-group), *Tichorhinus antiquitatis* Blum. (K). **Artiodactyla:** (?) *Sus scrofa* L., (?) *Cervus elaphus* L., (?) *C. maral* Ogilby (S), *Capreolus capreolus* L., *Rangifer tarandus* L., *Bos primigenius* Boj. (K), *Bison priscus* Boj., *Ovibos moschatus* Zimm. (K), *Ovis* sp. (S), *Capra ibex* L., *Rupicapra rupicapra* L. (K). **Proboscidea:** *Elephas primigenius* Blum. (K).

Interstadial LGL$_{2/3}$: Pin Hole Cave, Derbyshire, England.

Ref.—Armstrong (1931). See p. 135. Fauna is being studied further by Dr. J. W. Jackson.

Age.—Determined geologically. *c.* 60–30,000 years B.P.

Remarks.—Fauna on the whole cold, with milder oscillation in the middle, but reindeer persisting.

Fauna.—(A) Lower horizon with abundant reindeer, mammoth and woolly rhinoceros, and with arctic fox and arctic hare.

(B) Middle horizon with abundant bison and horse, and with red deer and reindeer.

(C) Upper horizon with abundant reindeer, arctic fox and arctic hare, and few bison and horse.

Interstadial LGL$_{2/3}$ (late): Petersfels, near Engen, Lake Constance Area, South-west Germany.

Ref.—Toepfer in Peters, see p. 76.

Age.—Determined geologically. *c.* 33,000 years B.P.

Remarks.—Subarctic forest with some open country, tundra or steppe. Climate becoming colder on approach of LGl$_3$.

Fauna.—**Insectivora:** *Talpa europæa* L., *Sorex araneus* L., *S. minutus* L., *Neomys fodiens* Pall., *Crocidura russula* Herm., *Erinaceus europæus* L. **Carnivora:** *Ursus arctos* L., *Canis lupus* L., *Vulpes vulpes* L., *V. lagopus* L., *Meles meles* L., *Mustela nivalis* L., *Putorius eversmanni* Less., *Gulo gulo* L., *Felis catus* L., *F. leo spelæa* Goldf., *Lynx lynx* L. **Rodentia:** *Lepus timidus* L., *Lagomys pusillus* Pall., *Sicista montana* Méh., *Cricetus cricetus* L., *Dicrostonyx torquatus* Pall., *Evotomys glareolus* Schreb., *Microtus ratticeps* Keys.

& Blas., *M. agrestis* L., *M. arvalis* Pall., *Arvicola terrestris* L., *Citellus rufescens* Keys. & Blas., *Marmota marmota* L., *Castor fiber* L. **Perissodactyla:** *Equus przewalskii* Pol. **Artiodactyla:** *Sus scrofa* L., *Cervus elaphus* L., *C.* cf. *maral* Ogilby, *Capreolus capreolus* L. (large form), *Rangifer tarandus* L. ("Canadian type," cf. *arcticus* Rich.), *Bison* or *Bos* sp., *Capra ibex* L., *Rupicapra rupicapra* L.

Last Glaciation, Phase 3: Balver Höhle, Westphalia, North-west Germany.

Ref.—Andrée (1939).

Age.—A superficial deposit, almost certainly LGl_3. *c.* 23,000 B.C.

Remarks.—Subarctic forest fauna (less continental conditions in North-west Germany!)

Fauna.—**Carnivora:** *Ursus spelæus* L., *Vulpes vulpes* L., *Mustela* sp., *Felis catus* L. **Rodentia:** *Lepus* sp., *Castor fiber* L. **Perissodactyla:** *Tichorhinus antiquitatis* Blum. **Artiodactyla:** *Sus scrofa* L., *Rangifer* sp. **Proboscidea:** *Elephas primigenius* Blum.

Last Glaciation, Phase 3 (Late): Hohler Stein, Westphalia, North-west Germany.

Ref.—Andrée (1931).

Age.—A superficial deposit just antedating Postglacial. *c.* 18,000 B.P. or slightly later.

Remarks.—Subarctic forest fauna like Balver Höhle, but mammoth has disappeared.

Fauna.—**Carnivora:** *Ursus spelæus* Ros., *Canis lupus* L., *Vulpes vulpes* L., *V. lagopus* L., *Meles meles* L., *Mustela* sp., *Felis catus* L. **Rodentia:** *Lepus* sp., *Arvicola amphibius* L., *Castor fiber* L. **Perissodactyla:** *Equus* sp. **Artiodactyla:** *Sus scrofa* L., *Cervus elaphus* L., *Alces alces* L., *Capreolus capreolus* L., *Rangifer* sp., *Bos primigenius* Boj.

BRITISH MOLLUSCA.

Note.—The lists have been compiled by Mr. Day Kimball, F.G.S. With the exception of Stutton, they are based on lists given to him by Mr. A. S. Kennard, A.L.S., whose work on the British Land and Freshwater Mollusca has made this field peculiarly his own. I cannot express too strongly my gratitude to Mr. Kennard for his kindness in thus allowing me to use his results in the following lists, especially as they contain many corrections, additions and much unpublished material. Similarly I am indebted to Mr. Kimball for his permission to publish his list of the Stutton fauna and for his valuable résumé.

The following localities, all of interglacial age, have been included:

Antepenultimate Interglacial.—Cromer Forest Bed (see p. 105), localities West Runton (R) and Sidestrand (Si) (Reid, 1890, pp. 155, 161); Little Oakley, near Harwich (new, Kennard det.).

Penultimate Interglacial.—Swanscombe (see p. 121), Lower Gravel and Loam (Sl) and Middle Gravel (Sm) (Kennard, in Swanscombe Rep., 1938); Clacton-on-Sea (Cl) (Kennard, in Warren, 1923, 1935; see p. 123); Grays Thurrock (G) (Kennard, MS. list; see p. 123).

Last Interglacial.—Peterborough Gravels (P), Overton-Waterville and Woodston sites; and Cambridge Gravels (Ca), Barnwell Abbey and Grantchester sites (Kennard, 1922, pp. 120–130); Stutton, near Harwich (St) (Kimball det., also Kennard, 1922, p. 132); West Wittering, Bracklesham Bay, Sussex (W) (Johnson, 1901; Reid, 1892, 1893); Admiralty section, London (A) (Abbott, 1892).

Postglacial.—Various deposits postdating LGl_3 (Kennard det.).

Living.—Species now living in Britain.

"+".—In interglacials, present in all localities quoted.

Mr. Day Kimball has come to the following conclusions regarding the Pleistocene Mollusca of Britain:

"Of the two sources of change which affected the Pleistocene mammals (phylogenetic evolution and migration), it would seem that the first played an extremely restricted part in determining the molluscan fauna. The outburst of evolutionary development appears to have taken place at an earlier date among land and freshwater mollusca than it did among the mammals and already to have slowed down to such an extent that little more than subspecific differentiation occurred during the Pleistocene. But, if we concentrate on a semi-isolated area like Great Britain, the effects of the other factor, migration, appear extremely marked. That this should be so is understandable if we bear in mind two circumstances. First, that each major glacial phase must have re-united Britain to the Continent and each interglacial phase have produced a similar isolation to that which exists to-day. Second, that with creatures like snails whose rate of dispersal must be extraordinarily slow, it may well have been a matter of chance which species did, and which did not, succeed in returning before island conditions were restored, to supplement the depauperized faunule that must, presumably, have resulted from any extensive glaciation of the British Isles. Of the reality of such (more or less 'accidental') changes the following lists appear to offer substantial evidence."

Land mollusca.	Ante-penultimate Interglacial.	Penultimate Interglacial.	Last Interglacial.	Post-glacial.	Living.
Pomatias elegans (Müller)	..	..	..	+	+
Acme lineata (Drap.)	..	..	..	+	+
Carychium minimum Müller	R	+	+	+	+
C. tridentatum (Risso)	..	Sl, Sm	St	+	+
C. ovatum Sandbg.	R, O	..	..	..	..
Succinea putris (Linné)	R	Sl, Cl	Ca, St	+	+
S. elegans Risso	..	Sl	Ca, St, W, A	+	+
S. pfeifferi Rossm.	R, O	+	P, Ca, St, W	+	+
S. oblonga Drap.	..	G	P, Ca, St, W	+	+
S. arenaria B.-C.	R	..	..	+	+
Cochlicopa lubrica (Müller)	R, O	+	+	+	+
Azeca goodalli (Fér.)	..	Sl, Sm, Cl	P, Ca, St ?	+	+
Ena montana (Drap.)	..	Sl, Cl	P, Ca	+	+
E. obscura (Müller)	..	..	Ca	+	+
Abida secale (Drap.)	..	..	..	+	+
Lauria cylindracea (da Costa)	..	..	W	+	+
L. anglica (Wood)	..	..	..	+	+
Pupilla muscorum (Linné)	R, O	+	+	+	+

Land mollusca.	Ante-penultimate Interglacial.	Penultimate Interglacial.	Last Inter-glacial.	Post-glacial.	Living.
Vertigo pusilla Müller	..	Sl, G	P, W	+	+
V. angustior Jeff.	..	..	P, Ca, W	+	+
V. pygmaea (Drap.)	..	Sm, Cl	P, Ca, St, W	+	+
V. antivertigo (Drap.)	R	Sm, Cl, G	+	+	+
V. substriata (Jeff.)	..	..	..	+	+
V. moulinsiana (Dupuy)	..	Cl	Ca, St, W	+	+
V. genesii Gredler	..	..	..	+	+
V. concinna Scott	..	..	W	+	..
V. alpestris Alder	..	..	..	+	+
Columella edentula (Drap.)	..	Cl	P, W	+	+
Truncatellina britannica Pilsb.	..	Cl	P, Ca, A	+	+
Clausilia rugosa (Drap.)	R	+	Ca, St, W, A	+	+
C. parvula Fér.	..	..	P	..	..
C. pumila C. Pfeiffer	..	Sl, Sm	P, Ca, St	..	..
C. ventricosa (Drap.)	..	Sl, Cl, G	P	..	..
C. rolphii Turton	..	..	..	+	+
C. suttoni Westerlund	..	..	..	+	+
C. biplicata (Montg.)	..	..	..	+	+
C. laminata (Montg.)	..	Sm, G	..	+	+
Balea perversa (Linné)	..	..	Ca	+	+
Cecilioides acicula (Müller)	..	Sm	Ca	+	+
Pyramidula rupestris (Drap.)	..	..	..	+	+
Acanthinula aculeata (Müller)	..	Sl, Cl	P, Ca, W	+	+
A. lamellata (Jeff.)	..	..	Ca, W	+	+
Vallonia pulchella (Müller)	R	+	+	+	+
V. excentrica Sterki	O	+	P, Ca, St, W	+	+
V. costata (Müller)	..	Sl, Sm, Cl	P, Ca, St, W	+	+
V. tenuilabris (Brg.)	..	Sl, Sm	..	..	..
V. tenuilimbata (Sandbg.)	R	..	..	..	..
Punctum pygmæum (Drap.)	R	Sl, Cl, G ?	P, Ca, St, W	+	+
Gonyodiscus rotundatus (Müll.)	..	+	P, Ca, St, W	+	+
G. ruderatus (Hartm.)	R	+, G ?	P, Ca, St, W	+	..
Vitrea crystallina (Müller)	O	Sl, Sm, Cl	+	+	+
Retinella nitidula (Drap.)	..	+, G ?	+	+	+
R. pura (Alder)	..	..	..	+	+
R. radiatula (Alder)	..	+, G ?	P, Ca, St	+	+
R. petronella (L. Pfeiffer)	..	..	..	+	..
Oxychilus cellarium (Müller)	..	Cl	Ca, St	+	+
O. alliarium (Miller)	..	..	Ca	+	+
O. rogersi (B. Woodward)	..	..	..	+	+
O. draparnaldi (Beck)	..	..	..	+	+
Zonitoides nitidus (Müller)	R	+	+	+	+
Z. excavatus (Alder)	..	Cl	..	+	+
Vitrina pellucida (Müller)	..	..	..	+	+
V. major (Fér.)	..	..	..	..	+
V. pyrenaica (Fér.)	..	..	..	..	+
V. elongata (Drap.)	R, O	..	..	..	..
Limax sp.	R	Sl, Sm	St, W	+	+
Arion sp.	..	..	St, W	+	+
Euconulus fulvus (Müller)	R	Cl	Ca, St, W	+	+
Fruticicola fruticum (Müller)	..	..	Ca, St	..	+
Helicella itala (Linné)	..	Cl, G	Ca	+	+
H. virgata (da Costa)	..	G	..	+	+

Land mollusca.	Ante-penultimate Interglacial.	Penultimate Interglacial.	Last Inter-glacial.	Post-glacial.	Living.
H. caperata (Montg.)	..	..	..	+	+
H. crayfordensis (K. & W.)	O	+	P, Ca, A	..	..
H. striata (Müller)	..	..	P, Ca	..	..
Cochlicella acuta (Müller)	..	..	..	+	+
Monacha cartusiana (Müller)	..	..	..	+	+
M. granulata (Alder)	..	Sm ?	..	+	+
Hygromia hispida (Linné)	R	Sl, Sm, Cl	+	+	+
H. liberta (Westerlund)	..	..	Ca, St	+	+
H. striolata (C. Pfeiffer)	..	..	..	+	+
H. revelata (Michaud)	..	..	..	+	+
Vortex lapicida (Linné)	..	Cl	Ca, St	+	+
Arianta arbustorum (Linné)	R	+	P, Ca, St, W	+	+
Helicodonta obvoluta (Müller)	..	..	Ca,	+	+
Helix nemoralis Linné	R	+	P, Ca, St, W	+	+
H. hortensis Müller	..	Cl	St	+	+
H. aspersa Müller	..	..	..	+	+
H. pomatia Linné	..	..	..	+	+

Fresh water mollusca.	Ante-penultimate Interglacial.	Penultimate Interglacial.	Last Inter-glacial.	Post-glacial.	Living.
Theodoxus fluviatilis (Linné)	..	..	..	+	+
T. cantianus K. & W.	..	Sm	..	..	..
Viviparus viviparus (Linné)	..	..	..	+	+
V. fasciatus (Müller)	..	..	..	+	+
V. diluvianus (Kunth)	..	Sm, Cl ?	..	..	..
V. gibbus (Sandbg.)	R	..	..	..	..
Valvata cristata Müller	R, Si	+	+	+	+
V. piscinalis (Müller)	..	Sm ?, Cl, G	+	+	+
V. andreana Menzel	+	Sl, Sm, Cl ?	..	..	..
V. antiqua Morris	..	Sm, Cl, G	..	..	..
V. macrostoma Mörch	..	Cl ?	P, Ca	?	+
V. naticina Menke	Si, O	Sm	..	..	..
V. woodwardi Kennard	R	..	..	..	..
Hydrobia ventrosa (Montagu)	..	..	W	+	+
H. radigueli (Bourgt.)	..	Sm, Cl, G	P, St, W	..	..
Bythinella steinii (Martens)	R	..	..	?	+
Belgrandia marginata (Michaud)	R, O	Sm, Cl, G	+	..	..
Pseudamnicola confusa (Frauenfeld)	..	Cl	St, W	+	+
Nematurella runtoniana (Sandbg.)	R, O	..	..	..	..
Bithynia tentaculata (Linné)	Si	+	+	+	+
B. inflata (Hans)	R, O	Sl, Sm, Cl	P, W	..	..
B. leachii (Sheppard)	..	..	..	+	+
Assiminea grayana Fleming	..	..	..	+	+
Physa fontinalis (Linné)	R	Cl	P, Ca, W	+	+
P. hypnorum (Linné)	..	Cl	P, Ca, W	+	+
Ancylus lacustris (Linné)	R, Si	Sm, Cl, G	Ca, St, W	+	+
A. fluviatilis (Müller)	R, O	+	P, Ca St, W	+	+
Lymnaea stagnalis (Linné)	R, Si	+	P, Ca, W	+	+
L. palustris (Müller)	R	+	+	+	+
L. glabra (Müller)	..	Cl	W	+	+
L. truncatula (Müller)	+	+	+	+	+
L. peregra (Müller)	R, O	+	+	+	+
L. auricularia (Linné)	..	..	..	+	+

Fresh water mollusca.	Ante-penultimate Interglacial.	Penultimate Interglacial.	Last Interglacial.	Post-glacial.	Living.
Myxas glutinosa (Müller)	R	..	..	+	+
Planorbis corneus (Linné)	R	Sl, Sm, G ?	St	+	+
P. planorbis (Linné)	R	Cl, G	+	+	+
P. carinatus Müller	R	+, G ?	P, Ca, W, A	+	+
P. leucostoma Millet	+	Sl, Cl, G	+	+	+
P. vortex (Linné)	R	+	+	+	+
P. vorticulus Troschel	R	Sm, G	..	+	+
P. albus Müller	R, Si	+	St	+	+
P. acronicus Fér.	R	..	..	+	+
P. laevis Alder	+	+	P, Ca, St, W	+	+
P. crista (Linné)	+	+	+	+	+
P. contortus (Linné)	R	Sm, Cl, G	P, Ca, St, W	+	+
P. complanatus (Linné)	R	+	Ca, St, W, A	+	+
Segmentina nitida (Müller)	R, Si	Cl, G ?	Ca, St, W	+	+
Unio pictorum (Linné)	R	Sm, G	P, Ca, St	+	+
U. tumidus Retzius	Si	Sm, Cl, G	St	+	+
U. cantianus K. & W.	Si	Sm	..	..	..
U. littoralis Cuvier	...	+	P, Ca, St, A	..	..
U. auricularia (Spengler)	..	..	..	+	..
U. margaritifera (Linné)	..	..	..	+	+
Anodonta anatina (Linné)	R	Sl, Cl	St	+	+
A. cygnea (Linné)	R	G	..	+	+
A. minima Millet	..	G	..	+	+
Dreissena polymorpha (Pallas)	..	..	..	+	+
Corbicula fluminalis (Müller)	R	Sm, Cl ?, G	Ca, St, W	..	..
Sphaerium rivicola (Lamarck)	R	Sm	..	+	+
S. solidum Normand*	O	Sm ?	..	..	..
S. bulleni Kennard*	R, Si	Sm ?	..	..	..
S. corneum (Linné)	R, Si	+	+	+	+
S. lacustre (Müller)	..	..	Ca	+	+
Pisidium amnicum (Müller)	+	+	P, Ca, St, W	+	+
P. astartoides Sandbg.	+	Sm, Cl, G	St ?	..	..
P. cinereum Alder	+	Sm, Cl	P, Ca, St, W	+	+
P. supinum A. Schmidt	+	Sm, Cl, G	Ca, St	+	+
P. henslowanum (Sheppard)	R, Si	Sm, Cl, G	P, Ca, St	+	+
P. subtruncatum Malm	+	Sm, Cl, G	P, Ca, St, W	+	+
P. lilljeborgi Clessin	R	..	..	+	+
P. pulchellum Jenyns	R	..	W	+	+
P. obtusale C. Pfeiffer	..	Sm, Cl	St, W	+	+
P. nitidum Jenyns	+	Sm, Cl, G	P, Ca, St, W	+	+
P. milium Held	R, Si	Sm, Cl	P, Ca, W	+	+
P. hibernicum Westerlund	..	Sm	..	+	+
P. personatum Malm	..	Sm, Cl	P, St	+	+
P. conventus Clessin	..	..	..	?	+
P. moitessierianum Paladilhe	+	Sm, G	St	+	+
P. tenuilineatum Stelfox	..	Sm	..	?	+
P. vincentianum B. Woodward	..	..	..	+	..

* Either *S. solidum* or *S. bulleni* present in Sm.

D. THE TIME-RATE OF EVOLUTION IN THE PLEISTOCENE.

If one considers the preceding lists of mammals as a whole, the most striking change that occurred in the course of the Pleistocene was the increase of the "cold" component of the fauna, which reached a climax during the Last Glaciation. It is natural, therefore, that pure palæontologists, like Hinton, Kennard, Stehlin and others, interpreted the faunal evidence as meaning that the maximum of cold was reached in the upper Pleistocene. The geological evidence, as exposed in this work, has since shown that the *climate* of the Antepenultimate and Penultimate Glaciations was just as cold as that of the Last. Since the fact that the mammals "look" coldest during the Last Glaciation cannot be disputed, the only conceivable explanation appears to be that the fauna became increasingly adapted to cold conditions in the course of the Pleistocene. This interpretation is well borne out by the evidence.

Of the two factors which brought about the adaptation of the fauna to the cold phases, one, migration, has been discussed on pp. 253–256. The other factor, phylogenetic evolution, though less conspicuous, is of even greater interest, since it throws some light on the time-rate of evolution of species in general.

For the purpose of studying the evolution of Pleistocene species it is necessary to select lineages of descent which can be regarded as reasonably certain. The requirements are (*a*) that the number of specimens on which the lineage relies is large enough in each deposit to account for individual and geographical variation, and (*b*) that the chronological succession of the forms is reliably known and covered by a large number of deposits of different age. These requirements are fulfilled for comparatively few species only, at any rate for the time being. The following lineages may be regarded as approximately correct. Slight modifications may become necessary in the future as contemporaneous geographical races become known from the various climatic phases.*

Some Lineages.—(1) *Brown Bears.*—*Ursus ? arvernensis* (Villafr.)⟶ *arvernensis* (Mosbach, $ApGl_1/_2$)⟶middle Pleist. intermediates usually classed as cf. *arctos*⟶*arctos* (upp. Pleist. and Recent). Partly teste Stehlin (1932).

(2) *Cave Bears.*—*Ursus ? etruscus* (Villafr.)⟶*deningeri* (ApIgl, $ApGl_1/_2$)⟶*suessenbornensis* ($ApGl_2$)⟶cf. *spelæus* (PIgl)⟶*spelæus* (upp. Pleist.). Partly teste Stehlin (1932).

(3) *Striped Hyænas.*—*Hyæna arvernensis* (Villafr.)⟶*intermedia* and *antiqua* (low. Pleist.)⟶*prisca* (low. Pleist.)⟶*hyæna* L. (Recent, not in Europe). Partly teste Pilgrim (1932).

(4) *Spotted Hyænas.*—*Hyæna perrieri* (Villafr., low. Pleist.)⟶cf. *spelæa* (mid. Pleist.)⟶*crocuta* with race *spelæa* (mid. and upp. Pleist.). Partly teste Pilgrim (1932), Stehlin (1932).

(5) *Voles.*—*Mimomys newtoni* ($EGl_1/_2$)⟶*M. majori* (ApIgl)⟶

* The difficulty of nomenclature comes in here. It is difficult to design a satisfactory nomenclature for Recent geographical races. With fossil forms it is even worse, partly because of the practice of palæontologists to treat races, subspecies and ecological varieties as taxonomic species, and partly because the time-element cannot be expressed in our present trinomial nomenclature.

Arvicola greeni ($ApGl_1$)——→*A. præceptor* (PIgl). A parallel lineage: *Mimomys pliocœnicus* (Villafr. to $EGl_{1/2}$)——→*M. intermedius* (ApIgl)——→ *Arvicola bactonensis* ($ApGl_1$). Both lineages change from *Mimomys* to *Arvicola* by losing the roots of the molars entirely. Teste Hinton (1926*a*).

(6) *Dicerorhine Rhinoceroses.—Dicerorhinus etruscus* (Villafr., low. Pleist.) ——→*merckii* (low., chiefly mid. Pleist. and LIgl), with a side-branch to *D. hemitœchus* (mid. Pleist. to $LGl_{1/2}$). Cp. Zeuner (1934).

(7) *Giant Deer.—Megaceros ? pliotarandoides* Aless. (Villafr.)——→*verticornis* (low. Pleist.)——→*germanicus* (mid. Pleist.)——→*giganteus* (upp. Pleist.). Partly teste Soergel (1927).

(8) *Straight-tusked Elephant.—Elephas meridionalis* (Villafr., low. Pleist. to $ApGl_1$)——→*antiquus* (low. and mid. Pleist.)——→late *antiquus* (LIgl). Teste Soergel (1912).

(9) *Mammoth.—Elephas meridionalis* (Villafr., low. Pleist. to $ApGl_1$)——→ *trogontherii* (low. and mid. Pleist.)——→*primigenius* (LGl). Teste Soergel (1912).

Evolution of Pleistocene Elephants.—The two elephant lineages, diverging from *E. meridionalis*, are here given as elaborated by Soergel, who relied on Pohlig's earlier work. A different view is held by Osborn (1942), who regards the straight-tusked elephant and the mammoth as descendants of less closely related stocks of elephants. It is possible to defend this view if one restricts the species to "typical" material of *E. meridionalis, antiquus* and *primigenius*. If one considers, however, the whole material of many thousands of specimens—many of them transitional —which are available in European collections, one finds that—

(*a*) *E. meridionalis* appears to be the direct descendant of *E. planifrons* of the upper Pliocene of India (Osborn, 1942, p. 950).

(*b*) In the Villafranchian and the Early Glaciation, *E. meridionalis* is the typical form. *Antiquus*-like molars from this phase are advanced varieties of *E. meridionalis* (Soergel, 1912, p. 87), while a few *trogontherii*-like molars have been described by Zuffardi (1913) as *E. trogontherioides*. Other molars resemble *E. planifrons* Falc. and Cautl. (Hopwood, 1935).

(*c*) During the Antepenultimate Interglacial, elephants of the types "*meridionalis*," "*antiquus*" and "*trogontherii*" coexisted, though a late *meridionalis*-type was the most frequent (*E. m. cromerensis* Dép. and May). Records of "*E. primigenius*" refer to extreme *trogontherii*.

(*d*) During the Interstadial $ApGl_1/_2$, *E. antiquus* dominates. A few doubtful records of *E. trogontherii* exist (Mauer: Soergel, 1914).

(*e*) $ApGl_2$ has yielded *E. trogontherii* only (at Süssenborn), though with varieties tending towards *E. meridionalis*, and others towards *E. primigenius* (Soergel, 1912, p. 60). Wüst identified some molars as *E. meridionalis*.

(*f*) In the Penultimate Interglacial, both *E. antiquus* and *E. trogontherii* are present and, as a rule, readily distinguished. Many molars are transitional, however. *E. antiquus* is the more frequent species during this temperate phase.

(*g*) In the Penultimate Glaciation, an advanced type of *E. trogontherii* is present, with molars varying from typical *trogontherii* to specimens indistinguishable from *E. primigenius*.

(*h*) In the upper Pleistocene, *E. antiquus* and *E. primigenius* are two

clearly distinguished species (cp. Zeuner, 1944). The former occurs in temperate, chiefly forest, biotopes, the latter in steppe and tundra biotopes. Overlap is rare.

The general trend in this group of elephants was to develop molars with narrower and more numerous grinding lamellae, which enabled their owners to take harder food. This was advantageous to elephants living in, or spreading into, the temperate zone of climate. Consequently we find that the evolution of the more efficient grinders is coupled with the expansion of our group of elephants over the temperate and parts of the cold zones of the northern hemisphere (see Osborn, 1942, pls. 21–23). Thus, these elephants appear to afford a parallel to the voles. Hinton's words (1926*a*, p. 31) apply almost literally to the *meridionalis*-stock of elephants: They appear "to have discovered the nutritive value of the coarser vegetable substances, such as moss, grass, tough leaves, bark and roots, and by degrees they substituted such unattractive provender for the softer and more succulent fruits, berries, nuts, tender foliage and green shoots eaten by their ancestors and less enterprising rivals. Leaving dainties to others, they thus tapped vast and never-failing food supplies which have in the course of time enabled their descendants, the Microtinæ, to colonize the Holarctic region more thoroughly and more completely than any of the related groups."

In particular, the succession, (*a*) to (*h*), reveals two remarkable facts. First, throughout the late Villafranchian and early Pleistocene, a great variability is observed. Although a standard type of *E. meridionalis* exists, extreme variants are found ranging from the more primitive *planifrons*-type (*e.g.* at Piltdown, Hopwood (1935); Osborn, 1942, p. 964) to the more advanced *antiquus*- and *trogontherii*-types. In the middle Pleistocene, the more primitive types like *planifrons* and *meridionalis* have vanished; the variation now ranges from *antiquus* to *trogontherii*, with many intermediate specimens. Finally, in the upper Pleistocene, the intermediates have dropped out; *E. trogontherii* has developed into *E. primigenius*, and it and *E. antiquus* are two entirely distinct species.

Secondly, while these changes take place, the *antiquus*-lineage becomes increasingly associated with the forest-biotope of the interglacial phases, while the *trogontherii-primigenius*-lineage becomes characteristic of the open country, and finally of loess-steppe and tundra. It is in *E. primigenius*, which relied on the roughest type of food, that the molars have developed into the most efficient grinders found among elephants. From the Penultimate Glaciation onwards, *E. trogontherii-primigenius* appears to have withdrawn to the colder north and east of the Old World during the temperate phases, while *E. antiquus* withdrew southwards during the cold phases.

It is very difficult to explain this evidence in any other way but Soergel's, *i.e.* by admitting that, from a *meridionalis*-stock of forest-elephants, two new species emerged gradually in the course of the Pleistocene, one adapted to temperate forests (and therefore less divergent from the original stock—*E. antiquus*), and one adapted to the new, periglacial types of environment (feeding on coarse, low-growing vegetation, with highly-specialized grinders, and living frequently in a cold climate, with thick fur and other adaptations —*E. primigenius*).

Other Instances of Evolution of New Species.—This instance of the evolution of the elephants during the Pleistocene, which resulted in an

adaptation of essential organs to the prevailing conditions of life, does not stand alone. From the instances of lineages given above, nos. (5), the voles, and (6), the dicerorhine rhinoceroses, afford close parallels. In both we find that the molars become adapted to coarser food. In the European voles the advance from molars that cease to grow in the adult, to rootless molars which grow throughout life, is made gradually during the lower Pleistocene (see Hinton, 1926*a*), when the periglacial biotopes developed in Europe for the first time. It is made in several lineages independently, and secures efficient grinders for the entire life-time of the individual.

In the rhinoceroses the Villafranchian and lower Pleistocene *Dicerorhinus etruscus* produced two variants which are present, together with the ancestral type, in faunas of the age of the Antepenultimate Glaciation or the Antepenultimate Interglacial. These are *D. merckii* and *D. hemitœchus*.* The former develops into a forest or parkland form and a companion of *E. antiquus*. The latter with its high-crowned molars and premolars became a denizen of the steppe, as was shown by Wüst (1922), and this view is confirmed by the shape of the skull, which indicates a grass-feeder (Zeuner, 1934, p. 51). In the late Pleistocene, it followed the mammoth on to the tundra (finds of frozen bodies of *D. hemitœchus* in Siberia), but generally speaking it was more tolerant of warmth than the mammoth, since it occurs in interglacial deposits also. Thus, *D. merckii* and *hemitœchus* appear to have evolved in much the same way as *E. antiquus* and *primigenius*. The woolly rhinoceros (*Tichorhinus antiquitatis*), however, was a steppe and tundra form which immigrated into Europe from the east.

Only one more of the lineages summarized above can be linked with the great changes of environment during the Pleistocene, that of the cave bear (no. 2). This species, too, developed into an open-country form, though it never became an exclusive member of the "cold" faunas. It is found in steppe faunas of the cold type as in those of the interglacial type, and it was partial to mountain-prairies.

On the remaining lineages (brown bear, hyænas, giant deer) no comment can be made at present.

Species-Rank of Late Pleistocene Forms.—In all the lineages quoted, however, the earliest and the latest stages are sufficiently different to be regarded as distinct taxonomic species. In the case of the voles, the passage to a new genus has been observed, but the morphological step was small, and the reception of the descendant into another genus entirely due to the definition of this genus. But among the elephants the mammoth differs so widely from its brother-species, *E. antiquus*, and from its ancestor, *E. meridionalis*, that many workers place it in a different genus. The morphological difference here is certainly so great that it is unanimously regarded at least as of species rank, and yet the change has proved to be the result of gradual evolution in the course of the Pleistocene.

Time-Rate of Evolution.—Now, the absolute chronology affords a means of dating these morphological changes, and of assigning time to the processes of evolution. The period from the beginning of the Pleistocene to the upper Pleistocene elapsed while new species of elephants, rhinoceroses, bears, etc., were evolved. Since these lineages were taken from various orders and since they show roughly the same rate of change, or less, than the

* *D.* cf. *hemitœchus* in Mosbach, teste Wüst (1922, p. 686).

elephants, it appears that, at least in these instances, 500,000 years were required for the evolution of a new species. It remains to be studied whether, in other groups, species have evolved at a faster rate. Evidence afforded by some insects (Zeuner, 1943) points to approximately the same rate, whilst other insects (Zeuner, 1943, p. 174) and mollusca (see Kimball, this work) have preserved their characters almost unmodified throughout the Pleistocene. With due caution it may be suggested, therefore, that half a million years is a fast rate for the gradual evolution of a new species as suggested by palæontological evidence.

The few figures suggested in the present chapter are merely intended to show that the chronology of the Pleistocene, both the climatic one and that in years, has a promising field of application in biology. Research bearing on evolution has occupied many workers in recent years, yet all results, however valuable in their proper sphere, have suffered from the handicap that nobody knew how much time was required by evolution in nature. The careful working-out of lineages in the light of absolute chronology, as shown in a very sketchy manner in these concluding paragraphs, opens a way to attack this important question, and to contribute some new facts to the discussion of the problems of evolution. The essential pre-requisite for such work is, of course, a reliable chronology which—as I hope to have shown in the present book—can be established by means of a combination of palæoclimatological and astronomical methods.

BIBLIOGRAPHY

CHAPTER I

ANDERSSON, J. G. 1906. Solifluction, a component of subaërial denudation. J. Geol., Chicago, **14**, pp. 95–112.

BLANCKENHORN, M. 1895. Pseudoglaziale Erscheinungen in den deutschen Mittelgebirgen. Zs. deutsch. geol. Ges., Berlin, **47**, pp. 576–581.

BREUIL, H. 1934. De l'importance de la solifluction dans l'étude des terrains quaternaires de la France et des pays voisins. Rev. Géogr. phys., Paris, **7**, pp. 269–331, pls. 18–24.

DÜCKER, A. 1933. Frostschub und Frosthebung. Centralbl. Min., etc., (B) **1933**, pp. 441–445.

——— 1937*a*. Über Strukturböden im Riesengebirge. Ein Beitrag zum Bodenfrost- und Lössproblem. Zs. deutsch. geol. Ges., Berlin, **89**, pp. 113–129, pls. 5, 6.

——— 1937*b*. Ist das Mass der Frosthebung unabhängig von der Temperatur ? Die Strasse, **1937**(5), pp. 138–140.

EBERL, B. 1930. Die Eiszeitenfolge im nördlichen Alpenvorlande. 427 pp., 2 pls. Augsburg.

ELTON, C. S. 1927. The Nature and Origin of Soil-Polygons in Spitsbergen. Quart. J. geol. Soc., London, **83**, pp. 163–194, pls. 10–12.

GARDNER, E. W. 1932. Some Problems of the Pleistocene Hydrography of Kharga Oasis, Egypt. Geol. Mag., London, **69**, pp. 386–421, pls. 26–31.

——— 1935. The Pleistocene Fauna and Flora of Kharga Oasis, Egypt. Quart. J. geol. Soc., London, **91**, pp. 479–518, pls. 30–34.

GEIKIE, J. 1894. The Great Ice Age. 3rd ed., 850 pp., 18 pls. London.

GRAHMANN, R. 1932. Der Löss in Europa. Mitt. Ges. Erdkunde, Leipzig, **1930–31**, pp. 5–24, pls. 1, 2.

GRIPP, K. 1924. Über die äusserste Grenze der letzten Vereisung in Nordwest-Deutschland. Mitt. geogr. Ges., Hamburg, **36**, pp. 159–245, 1 map.

——— 1927. Beiträge zur Geologie von Spitzbergen. Abh. Geb. Natwiss., Hamburg, **21**, pp. 1–38, pls. 1–7.

——— 1929. Glaciologische und geologische Ergebnisse der Hamburgischen Spitzbergen-Expedition, 1927. Abh. naturw. Ver., Hamburg, **22**, pp. 145–249, pls. 1–32.

——— and SIMON, W. C. 1934. Die experimentelle Darstellung des Brodelbodens. Naturwissenschaften, Berlin, **22**, pp. 8–10.

——— and TODTMANN, E. 1926. Die Endmoräne des Green-Bay-Gletschers auf Spitzbergen. Eine Studie zum Verständnis norddeutscher Diluvialgebilde. Mitt. geogr. Ges., Hamburg, **37**, pp. 43–75, 14 pls.

HAWKES, L. 1924. Frost Action in Superficial Deposits, Iceland. Geol. Mag., London, **61**, pp. 509–513, pl. 27.

HESS, H. 1904. Die Gletscher. 426 pp., 8 pls., 4 maps. Braunschweig.

HÖGBOM, B. 1914. Über die geologische Bedeutung des Frostes. Bull. geol. Inst. Upsala, **12**, pp. 258–390.

HUXLEY, J. S. 1925. Les " sols polygonaux " et l'évolution des phénomènes de dénudation dans les pays arctiques. Ann. Géogr. Paris, **34**, pp. 60–62.

——— and ODELL, N. E. 1924. Notes on Surface Markings in Spitsbergen. Geogr. J., London, **63**, pp. 207–229, 2 pls.

(IMPERIAL BUREAU OF SOIL SCIENCE.) 1934. Soil, Vegetation and Climate. Imp. Bur. Soil Sci., tech. Comm., Harpenden, **29**, 43 pp.

KESSLER, P. 1925. Das eiszeitliche Klima und seine geologischen Wirkungen im nicht vereisten Gebiete. 210 pp. Stuttgart.

KNOTHE, H. 1931. Spitzbergen. Eine landeskundliche Studie. Ergänzungshefte Petermann's Mitt., Gotha, **211**, 109 pp., 8 pls.

KÖPPEN, W. 1931. Grundriss der Klimakunde. 2nd ed., 388 pp., 9 pls. Berlin and Leipzig.

LEFFINGWELL, K. 1915. Ground-ice Wedges, the dominant form of ground-ice on the north coast of Alaska. J. Geol., Chicago, **23**, pp. 635–654.

LOW, A. R. 1925. Instability of Viscous Fluid-Motion. Nature, London, **115**, pp. 299–300.

LOZINSKI, W. v. 1912. Die periglaziale Fazies der mechanischen Verwitterung. C.R. Congr. géol. int. (Stockholm), (11) **2**, pp. 1039–1053.

PATERSON, T. T. 1940. The Effects of Frost Action and Solifluxion around Baffin Bay and in the Cambridge District. Quart. J. geol. Soc., London, **96**, pp. 99–130, pls. 5–6.

PENCK, A., and BRÜCKNER, E. [1901–]1909. Die Alpen im Eiszeitalter. 3 vols., 1189 + xxxvi pp., 31 pls. Leipzig.

POSER, H. 1933. Das Problem des Strukturbodens. Geol. Rundsch., Berlin, **24**, pp. 105–121.

REID, C. 1887. On the Origin of Dry Chalk Valleys and of Coombe Rock. Quart. J. geol. Soc., London, **43**, pp. 364–373.

ROBINSON, G. W. 1932. Soils, their Origin, constitution and classification. 390 pp. London.

SALOMON, W. 1916. Die Bedeutung der Solifluktion für die Erklärung deutscher Landschafts- und Bodenformen. Geol. Rundsch., Berlin, **7**, pp. 30–41.

SCHOSTAKOWITSCH, W. B. 1927. Der ewig gefrorene Boden Sibiriens. Zs. Ges. Erdkunde, Berlin, **1927**, pp. 394–427.

SELZER, G. 1936. Diluviale Lösskeile und Lösskeilnetze aus der Umgebung Göttingens. Geol. Rundsch., Berlin, **27**, pp. 275–293.

SLATER, G. 1926. Glacial Tectonics as reflected in disturbed drift deposits. Proc. geol. Assoc., London, **37**, pp. 392–400.

——— 1927. Studies in the Drift Deposits of South-west Suffolk. Proc. geol. Assoc., London, **38**, pp. 157–216, 3 pls.

SOERGEL, W. 1919. Lösse, Eiszeiten und paläolithische Kulturen. 177 pp., 1 pl. Jena.

——— 1921. Die Ursachen der diluvialen Aufschotterung und Erosion. Berlin.

——— 1923. Diluviale Flussverlegungen und Krustenbewegungen. Fortschr. Geol. Palæont., Berlin, **5**, 388 pp., 10 pls.

——— 1926. Excursion ins Travertingebiet von Ehringsdorf. Palæont. Zs., Berlin, **8**, pp. 7–33.

——— 1929. Das Alter der Sauerwasserkalke von Cannstatt. Jber. Mitt. geol. Verg., Stuttgart, **18**, pp. 83–153.

——— 1932. Diluviale Frostspalten im Deckschichtenprofil von Ehringsdorf. Fortschr. Geol. Palæont., Berlin, **36**, pp. 439–460.

——— 1936. Diluviale Eiskeile. Zs. deutsch. geol. Ges., Berlin, **88**, pp. 223–247.

STOLTENBERG, H. 1935. Der Dauerfrostboden. Geol. Rundsch., Stuttgart, **26**, pp. 412–423.

TROLL, K. 1926. Die jungglazialen Schotterfluren im Umkreis der deutschen Alpen. Forsch. deutsch. Landes- u. Volksk., Stuttgart, **24** (4), 256 pp., 6 pls.

WIEGNER, G. 1929. Boden und Bodenbildung. 5th ed., 98 pp. Dresden and Leipzig.

WOOD, S. V. 1882. On the newer Pliocene Period in England. Quart. J. geol. Soc., London, **38**, pp. 667–745, pl. 26.

ZEUNER, F. E. 1932. Die Schotteranalyse. Ein Verfahren zur Untersuchung der Genese von Flussschottern. Geol. Rundsch., Berlin, **24**, pp. 65–121.

ZEUNER, F. E. 1934*a*. Das Klima des Eisvorlandes in den Glazialzeiten. N. Jahrb. Min., etc., Stuttgart, B.-Bd. (B) **72**, pp. 367–398.
——— 1934*b*. Die Beziehungen zwischen Schädelform und Lebensweise bei den rezenten und fossilen Nashörnern. Ber. naturf. Ges. Freiberg i. Br., **34**, pp. 21–80, pls. 1–8.
——— 1934*c*. Ein Toteisgebiet der Risseiszeit in Oberschlesien. In: Vom deutschen Osten, ed. by H. Knothe, pp. 379–394, pl. 20. Breslau.
——— 1935. Diluviale Frostspalten in Schlesien. Jber. geol. Verg. Oberschles., Gleiwitz, pp. 97–105.
——— 1936. Palæobiology and Climate of the Past. Probl. Palæont., Moscow, **1**, pp. 199–216.
——— 1937. The Climate of the Countries adjoining the Ice-sheet of the Pleistocene. Proc. Geol. Assoc., London, **48**, pp. 379–395.
——— 1938. The Department of Geochronology. In: Ann. Rep. London Univ. Inst. Archæol., **1**, pp. 29–46.
——— and SCHULTZ, G. 1931. Die Entwicklung des Entwässerungssystems des Landrückens zwischen Warthe und Oder seit der letzten Eiszeit. N. Jahrb. Min., etc., Stuttgart, B.-Bd. (B) **65**, pp. 197–290, pls. 13, 14.

CHAPTER II

ANTEVS, E. 1928. The Last Glaciation. Amer. geogr. Soc. Res. Ser., New York, **17**, 292 pp., 9 pls.
BECK, P. 1933. Über das schweizerische und europäische Pliozän und Pleistozän. Ecl. geol. Helv., Basle, **26**, pp. 335–437, pls. 13, 14.
——— 1936. Zur Revision der Quartärchronologie der Alpen. Verh. III int. Quart.-Konf. Wien, Sept., 1936, 13 pp.
——— 1937. Vorläufige Mitteilung über eine Revision des alpinen Quartärs. Ecl. geol. Helv., Basle, **30**, pp. 75–85, pl. 11.
——— 1939. Zur Geologie und Klimatologie des schweizerischen Altpalæolithikums. Mitt. naturw. Ges. Thun., 1939 (4), 41 pp.
BRYAN, K., and RAY, L. L. 1940. Geologic Antiquity of the Lindenmeier Site in Colorado. Smiths. misc. Coll., Washington, **99** (2), 76 pp., 6 pls.
BUBNOFF, S. v. 1936. Das Quartär Nord- und Mitteleuropas. In: Geologie von Europa, **2** (3), pp. 425–1489. Berlin.
CHAMBERLAIN, T. C., and SALISBURY, R. D. 1906. The Pleistocene or glacial period. In: Geology, **3**, pp. 327–516. London.
COLEMAN, A. P. 1926. Ice Ages, recent and ancient. 296 pp. London.
——— 1941. The Last Million Years; a history of the Pleistocene in North America, 216 pp. Toronto.
DIETRICH, W. O. 1932. Über den Rixdorfer Horizont im Berliner Diluvium. Zs. deutsch. geol. Ges., Berlin, **84**, pp. 193–221.
EBERL, B. 1928*a*. Zur Chronologie und Gliederung des Eiszeitalters im Bereiche des alpinen Glazials. Anthrop. Anz., Stuttgart, **5**, pp. 250–259.
——— 1928*b*. Zur Gliederung und Zeitrechnung des alpinen Glazials. Zs. deutsch. geol. Ges., Berlin, **80**, Monatsber., pp. 107–117.
——— 1930. Die Eiszeitenfolge im nördlichen Alpenvorlande. 427 pp., 2 pls. Augsburg.
ERB, L. 1936. Zur Stratigraphie des mittleren und jüngeren Diluviums in Südwestdeutschland und dem schweizerischen Grenzgebiet. Mitt. Bad. geol. Landesanst., Freiburg i. Br., **11** (6), pp. 1–34.
GAGEL, C. 1913. Die Beweise für eine mehrfache Vereisung Norddeutschlands in diluvialer Zeit. Geol. Rundsch., Berlin, **4**, pp. 319–362, 444–502, 588–591.
GALON, R. 1938. Versuch einer Klassifikation der Endmoränen im polnischen und deutschen Flachland. C.R. Congr. int. Géogr. Amsterdam, **1**, pp. 161–164.

Gams, H. 1930. Die Bedeutung der Paläobotanik und Mikrostratigraphie für die Gliederung des mittel-, nord- und osteuropäischen Diluviums. Zs. Gletscherkunde, Berlin, 18, pp. 279–336.

Girmounsky, A. W. 1931. Versuch einer vergleichenden Zusammenstellung der westeuropäischen, amerikanischen und russischen Schemen für die Gliederung der Quartärzeit. Zs. Gletscherkunde, Berlin, 19, pp. 29–49.

——— 1932. Die Probleme der unteren Grenze des Anthropozoikums und einige andere Fragen der Synchronisation der anthropozoischen Ablagerungen. Trans. 2nd internat. Conf. Study Quatern. Per. Europe, Leningrad-Moscow, 1, pp. 63–79.

——— 1936. Neue Versuche der Synchronisation der Quartärablagerungen von West und Osteuropa. Beitr. Kenntn. Quartärs USSR, Leningrad, pp. 50–65.

Gripp, K. 1940. Müssen gewisse jungeiszeitliche Endmoränenzüge im nördlichen Alpenvorland und in Norddeutschland als vom Eise überfahren angesehen werden ? Mitt. geogr. Ges. Lübeck, (2) 40, pp. 7–29.

Gutzwiller, A. 1912. Die Gliederung der Diluvialschotter in der Umgebung von Basel. Verh. naturf. Ges., Basel, 23, pp. 57–75.

Heck, H. 1930. Zur Fossilführung der Berliner Paludinenbank, ihrer Beschaffenheit und Verbreitung. Zs. deutsch. geol. Ges., Berlin, 82, pp. 385–404, pl. 8.

Heim, A. 1919. Geologie der Schweiz. Bd. 1. Molasseland und Juragebirge. 704 pp., 31 pls. Leipzig.

Hess von Wichdorff, H. 1915. Das masurische Interstadial. Jahrb. preuss. geol. Landesanstalt, Berlin, 35 (2), pp. 298–353, pls. 28–30.

Hug, J. 1917. Die letzte Eiszeit der Umgebung von Zürich. Vierteljahrsschr. naturf. Ges. Zürich, 62, pp. 125–142, pl. 5.

——— 1932. Zur Gliederung der Hochterrasse im Limmat- und Glattal. Ecl. geol. Helv., Basle, 25, pp. 264–265.

Hesemann, J. 1931a. Quantitative Geschiebebestimmungen im norddeutschen Diluvium. Jahrb. preuss. geol. Landesanstalt, Berlin, 51, pp. 714–758.

——— 1931b. Das Glazialdiluvium Dänemarks, Hollands und Norddeutschlands vom geschiebekundlichen Standpunkt aus. Geol. Rundsch., Stuttgart, 22, pp. 146–155.

——— 1934. Ergebnisse und Aussichten einiger Methoden zur Feststellung der Verteilung kristalliner Leitgeschiebe. Jahrb. preuss. geol. Landesanstalt, Berlin, 55, pp. 1–27.

——— 1935. Neue Ergebnisse der Geschiebeforschung im norddeutschen Diluvium (kristalline Geschiebe). Geol. Rundsch., Stuttgart, 26, pp. 186–198.

Jakovleff, S. A. 1932. Beitrag zur Karte der Ablagerungen des Quartaer-Systems des europäischen Teiles der USSR und der angrenzenden Gebiete im Masstabe 1 : 2,500,000. Trans. 2nd internat. Conf. Assoc. Study Quatern. Per. Europe, Leningrad and Moscow, 1, pp. 80–93, 1 map.

Jessen, K., and Milthers, V. 1928. Interglacial Freshwater Deposits in Jutland and North-west Germany. Danm. geol. Undersøg., Copenhagen, (2) 48, pp. 1–379, 30 pls., atlas.

Kay, G. F. 1928. The relative ages of the Iowan and Illinioan drift sheets. Amer. J. Sci., New Haven, (5) 16, pp. 497–518.

Klimaszewski, H. 1932. Some problems of the glaciation in Poland. Roczn. Polsk. Tow. geol., Cracow, 8 (2), pp. 227–236.

Knauer, J. 1928. Glazialgeologische Ergebnisse im Isargletscher-gebiet. Zs. deutsch. geol. Ges., Berlin, 80, Monatsber., pp. 294–303.

——— 1935. Die Ablagerungen der älteren Würm-Eiszeit (Vorrückungsphase) im süddeutschen und norddeutschen Vereisungsgebiet. Abh. geol. Landesuntersuchung, München, 21, 65 pp., 10 pls.

——— 1937. Sind die Pommerschen Moränen Vorrückungs- oder Rückzugsmoränen der Würmeiszeit ? Zs. Gletscherkunde, Berlin, 25, pp. 227–232.

——— 1938a. Die Mindel = Eiszeit, die Zeit grösster diluvialer Vergletscherung in Süddeutschland. Abh. geol. Landesuntersuchung, München, 29, pp. 35–45, pls. 1–3.

Knauer, J. 1938b. Über das Alter der Moränen der Zürich Phase im Linthgletscher-Gebiet. Abh. geol. Landesuntersuchung, München, 33, pp. 3–29, 7 pls.

Leighton, M. M. 1926. A notable Pleistocene section: the Farm Creek exposure near Peoria, Illinois. J. Geol., Chicago, 34, pp. 167–174.

Leverett, F. 1910. Comparison of North American and European glacial deposits. Zs. Gletscherkunde, Berlin, 4, pp. 241–295, 321–342.

——— 1926. The Pleistocene glacial stages: were there more than four? Proc. Amer. phil. Soc., Philadelphia, 65, pp. 105–118.

Madsen, V., and others. 1928. Summary of the Geology of Denmark. Danm. geol. Undersøg., Copenhagen, (5) 4, 219 pp., 2 pls.

Menzel, H. 1915. Über die spätglazialen Conchylien-Faunen Ostpreussens. Jahrb. preuss. geol. Landesanstalt, Berlin, 35 (2), pp. 354–365.

Milthers, V. 1934. Die Verteilung skandinavischer Leitgeschiebe im Quartär von Westdeutschland. Abh. preuss. geol. Landesanstalt, Berlin, (n.s.) 156, 74 pp., 2 pls.

Mirčink, G. 1928. La corrélation des dépôts Quaternaires de la Plaine Russe à ceux du Caucase. Izw. Assoc. naučn. issl. Inst., Moscow, 2, pp. 327–359.

——— 1930. Structure and Composition of Quaternary Deposits in the European Part of the USSR. Guide-book Excurs. 2nd int. Congr. Soil Science, Moscow, 1, pp. 1–6.

——— 1936. La corrélation entre les dépôts quaternaires continentaux de la plaine russe et les dépôts correspondants du Caucase et de la dépression ponto-caspienne. Beitr. Kenntnis Quartärs USSR, Leningrad-Moscow, pp. 15–36.

Münnich, G. 1936. Quantitative Geschiebeprofile aus Dänemark und Nordost-deutschland mit besonderer Berücksichtigung Vorpommerns. Abh. geol. palæont. Inst., Greifswald, 15, 52 pp.

Penck, A., and Brückner, E. 1909. See I, p. 280.

Premik, J. 1932. Über die Ausbildung und Gliederung des Diluviums im südwestlichen Teil Mittelpolens. Roczn. Polsk. Tow. geol., Cracow, 8 (2), pp. 1–50.

Reinhard, A. L. 1933. Die eiszeitliche Vergletscherung des Kaukasus und ihre Beziehung zu den Vergletscherungen der Alpen und des Altai. Trans. 2nd int. Conf. Assoc. Study Quat. Per. Europe, Leningrad-Moscow, 2, pp. 5–16.

——— 1936. Die Stratigraphie des alpinen Eiszeitalters nach P. Beck und A. Penck und der Kaukasus. Beitr. Kenntnis Quartärs USSR, Leningrad-Moscow, pp. 37–49.

Schmidle, W. 1914. Die diluviale Geologie der Bodenseegegend. Die Rheinlande, Braunschweig, 8, 113 pp., 7 pls.

Soergel, W. 1919. Lösse, Eiszeiten und paläolithische Kulturen. Jena. 177 pp., 1 pl.

Szafer, W. 1928. Zarys stratigrafji polskiego dyluwjum na podstawie florystycznej. [Essay of a stratigraphy of the Polish Pleistocene on a botanical basis.] Roczn. polsk. Tow. geol., Cracow, 5, pp. 1–15, 2 pls. (Article in German.)

——— 1931. The oldest Interglacial in Poland. Bull. Acad. Pol. Sci. Lett., Cracow, cl. math.-nat., (B) 1931, pp. 19–50, pl. 1.

Troll, K. 1925. Die Rückzugsstadien der Würmeiszeit im nördlichen Vorland der Alpen. Mitt. geogr. Ges. München, 18, pp. 281–292.

——— 1926. Die jungglazialen Schotterfluren im Umkreis der deutschen Alpen. Forsch. deutsch. Landes- u. Volkskunde, Stuttgart, 24 (4), 256 pp., 6 pls.

——— 1936. Die sogenannte Vorrückungsphase der Würm-Eiszeit und der Eiszerfall bei ihrem Rückgang. Mitt. geogr. Ges. München, 29, pp. 1–38.

Vardanianz, L. A. 1933. Zur Synchronisierung der Rückzugsstadien der letzten Vergletscherung des zentralen Kaukasus mit der Würm-Eiszeit der Alpen. Trans. 2nd int. Conf. Assoc. Study Quat. Per. Europe, Leningrad-Moscow, 2, pp. 17–23.

Vierke, M. 1937. Die ostpommerschen Bändertone als Zeitmarken und Klimazeugen. Abh. geol. palæont. Inst. Greifswald, 18, 34 pp.

Wahnschaffe, F., and Schucht, F. 1921. Geologie und Oberflächengestaltung des norddeutschen Flachlandes. 4th ed., 472 pp., 29 pls. Stuttgart.

WERVECKE, L. VAN. 1924. Das Alter der Sundgauschotter im Ober-Elsass. Zs. deutsch. geol. Ges., Berlin, 76, Monatsber., pp. 130–138.

——— 1927. Norddeutschland war wenigstens viermal vom Inlandeise bedeckt. Zs. deutsch. geol. Ges., Berlin, 79, Monatsber., pp. 135–155.

——— 1928. Bemerkungen über die "Warthe-Eiszeit," die Sölle der Letzlinger Heide und über eine fünfte Eiszeit in Norddeutschland. Zs. deutsch. geol. Ges., Berlin, 80, Monatsber., pp. 360–373.

——— 1931. Die Zahl der Vereisungen in den Alpen und in Mittel- und Norddeutschland. Forsch. Fortschr., Berlin, 7, p. 201.

——— 1933. Die Zahl der Vereisungen in Mittel- und Norddeutschland. Das Alter der Geschiebemergel bei Hamburg und Berlin. Jber. niedersächs. geol. Ver. Hannover, 25, pp. 201–228.

WOLDSTEDT, P. 1928*a*. Die Gliederung des nordeuropäischen Diluviums. C.R. Réun. géol. internat. Copenhague, 1928, pp. 209–223. 1 pl.

——— 1928*b*. Die Parallelisierung des nordeuropäischen Diluviums mit dem anderer Vereisungsgebiete. Zs. Gletscherkunde, Berlin, 16, pp. 230–241.

——— 1929. Das Eiszeitalter. 406 pp., 162 figs. Stuttgart.

——— 1930. Die nordamerikanischen Eiszeitbildungen verglichen mit denen Europas. Forsch. Fortschr., Berlin, 6, pp. 77–79.

——— 1935. Über den stratigraphischen Wert von Geschiebeuntersuchungen in Norddeutschland. Zs. deutsch. geol. Ges., Berlin, 87, pp. 360–369.

WRIGHT, G. F. 1911. The Ice Age in North America. 5th ed., 764 pp., pls. Ohio.

WRIGHT, W. B. 1937. The Quaternary Ice Age. 2nd ed., 478 pp., 23 pls. London.

ZEUNER, F. E. 1935. The Pleistocene Chronology of Central Europe. Geol. Mag., London, 72, pp. 350–376.

——— 1937. Chronologija pleistocena. [The chronology of the Pleistocene.] Glas srpska kralj. Akad., Belgrade, 177 (sect. 1, 87B), no. 7, 78 pp.

——— 1938. Die Chronologie des Pleistozäns. Bull. Acad. Serbe Sci. math. nat., Belgrade, (B) 4, 79 pp.

——— and SCHULZ, G. 1931. Die Entwicklung des Entwässerungssystems des Landrückens zwischen Warthe und Oder seit der letzten Eiszeit. N. J. Min., etc., Stuttgart, B.-Bd. (B) 65, pp. 197–290, pls. 13, 14.

——— and KIMBALL, D. 1944. The Terraces of the Rhine between Constance and Basle. (In the press.)

CHAPTER III

AULT DU MESNIL, G. D'. 1896 [Sept. 15]. Note sur le terrain quaternaire des environs d'Abbeville. Rev. mens. École Anthrop., Paris, 13 pp., 1 map, 2 figs.

BERGER, F. 1931. Diluviale Stratigraphie und Tektonik im Gebiete der oberen Neisse und der Steine. Jb. Preuss. geol. Landesanstalt, Berlin, 52, pp. 177–244.

BOUCHER DE PERTHES, M. 1849. Antiquités celtiques et antédiluviennes. Vol. I. 628 pp., 80 pls. Paris. (On the title page: 1847, but not published until 1849.)

——— 1859. Antiquités antédiluviennes. Réponse à MM. les antiquaires et géologues présents aux assises archéologiques de Laon. Bull. Soc. Antiqu. Picardie, Amiens, 1859 (2), 31 pp.

BOWLER-KELLEY, A. 1937. Lower and Middle Palæolithic Facies in Europe and Africa. 31 pp., 1 pl. Privately printed, for the Symposium of Early Man, Acad. nat. Sci. Philadelphia, March 17, 1937.

BRÄUHÄUSER, M. 1909. Beiträge zur Stratigraphie des Cannstatter Diluviums. Mitt. geol. Abt. K. württ. stat. Landesamt, Stuttgart, no. 6.

——— 1916. Neuere Aufschlüsse im Diluvium von Stuttgart-Cannstatt. Jber. Mitt. oberrhein. geol. Ver., (N.F.) 6.

BREDDIN, H. 1928. Die Höhenterrassen von Rhein und Ruhr am Rande des Bergischen Landes. Jb. preuss. geol. Landesanstalt, Berlin, 49, pp. 501–550, pl. 36.

BREDDIN, H. 1931. Flussterrassen und Löss am Niederrhein. Zs. deutsch. Geol. Ges., Berlin, 83, pp. 659–660.

BREUIL, H. 1934. De l'importance de la solifluxion dans l'étude des terrains quaternaires de la France et des pays voisins. Rev. Géogr. phys., Paris, 7, pp. 269–331, pls. 18–24.

——— 1936. Somme et Charente. Bull. Soc. archéol. hist. Charente, Angoulême, 14 pp.

——— 1937. La préhistoire. Rev. Cours Confér., 30th Dec., 1929, 20 pp. Imprimerie de Lagny.

——— 1939*a*. Le vrai niveau de l'industrie abbevillienne de la Porte du Bois (Abbeville). Anthrop., Paris, 49, pp. 13–34, 22 figs.

——— 1939*b*. The Pleistocene Succession in the Somme Valley. Proc. prehist. Soc., London (N.S.), 5, pp. 33–38.

BREUIL, H., and KOSLOWSKI, L. [1931–] 1932. Étude de stratigraphie paléolithique dans le nord de la France, la Belgique et l'Angleterre. La vallée de la Somme. Anthrop., Paris, 41, pp. 449–488 ; 42, pp. 27–47, 291–314.

COMMONT, V. 1909*a*. Les gisements paléolithiques de Saint-Acheul. Coupe du quaternaire dans la vallée de la Somme. C.R. Assoc. franç. Av. Sci., Paris, 37, pp. 454–465.

——— 1909*b*. L'industrie de l'age du renne dans la vallée de la Somme. Fouilles à Belloy-sur-Somme. C.R. Assoc. franç. Av. Sci., Paris, 37, pp. 634–643.

——— 1909*c*. Saint-Acheul et Montières. Mém. Soc. géol. Nord, Lille, 6 (3), 68 pp., 3 pls.

——— 1910*a*. Montières-les-Amiens (dépôts quaternaires). C.R. Assoc. franç. Av. Sci., Paris, 38, pp. 437–444.

——— 1910*b*. La faune quaternaire dans le nord de la France. C.R. Assoc. franç. Av. Sci., Paris, 38, pp. 445–449.

——— 1910*c*. Industrie des graviers inférieurs de la haute terrace de Saint-Acheul. C.R. Assoc. franç. Av. Sci., Paris, 38, pp. 774–777.

——— 1910*d*. L'industrie de l'age du renne dans la vallée de la Somme. C.R. Assoc. franç. Av. Sci., Paris, 38, pp. 798–802.

——— 1910*e*. Note préliminaire sur les terraces fluviatiles de la Vallée de la Somme. Ann. Soc. géol. Nord, Lille, 39, pp. 185–210.

——— 1910*f*. Les gisements paléolithiques d'Abbeville. Ann. Soc. géol. Nord, Lille, 39, pp. 249–292.

——— 1911*a*. Niveaux industriels et fauniques dans les couches quaternaires de Saint-Acheul et de Montières. C.R. Assoc. franç. Av. Sci., Paris, 39 (2), pp. 236–240.

——— 1911*b*. Les différents niveaux de l'industrie de l'age du renne dans les limons du Nord de la France. C.R. Assoc. franç. Av. Sci., Paris, 39 (2), pp. 241–242.

——— 1912*a*. La chronologie et la stratigraphie des dépôts quaternaires dans la vallée de la Somme. Ann. Soc. géol. Belg., Liége, 39, B156–B170.

——— 1912*b*. Chronologie et stratigraphie des industries protohistoriques, néolithiques et paléolithiques dans les dépôts holocènes et pléistocènes du nord de la France et en particulier de la vallée de la Somme. Remarques et comparaisons relatives aux loess et aux glaciations. Congr. int. Anthrop. Archéol. Préhist. Genève, 1912.

——— 1913*a*. Chronologie et stratigraphie des industries néolithiques et paléolithiques dans les dépôts holocènes et pléistocènes du Nord de la France. C.R. Assoc. franç. Av. Sci., Paris, 41, pp. 502–507.

——— 1913*b*. Les Hommes contemporains du renne dans la Vallée de la Somme. Soc. Antiqu. Picardie, 37, pp. 207–646.

GRAHMANN, R. 1925. Diluvium und Pliozän in Nordwestsachsen. Abh. Sächs. Akad. Wiss., Leipzig, math.-phys. Kl., 39 (4).

——— 1928. Über die Ausdehnung der Vereisungen Norddeutschlands und ihre Einordnung in die Strahlungskurve. Ber. Sächs. Akad. Wiss., Leipzig, math.-phys. Kl., 80, pp. 134–163.

GRAHMANN, R. 1932. Das Alter der "Hellerterrasse" und der Dünen bei Dresden. Mitt. Ver. Erdkunde, Dresden, 1931–32 (N.F.), pp. 85–97. Dresden, 1932.

——— 1933. Die Geschichte des Elbtales von Leitmeritz bis zu seinem Eintritt in das norddeutsche Flachland. Mitt. Ver. Erdkunde, Dresden (N.F.), 1932–33.

GRUPE, O. 1926. Tal- und Terrassenbildung im Gebiete der Werra-Fulda-Weser, und Soergel's Gliederung und absolute Zeitrechnung des Eiszeitalters. Geol. Rundsch., Berlin, 17 (3), pp. 161–196.

HELLER, F. 1936. Eine oberpliozäne Wirbeltierfauna aus Rheinhessen. N. Jahrb. Min., etc., Stuttgart, B.-Bd. (B) 76, pp. 99–160.

KEILHACK, K. 1921. Der Rabutzer Beckenton und das Alter seiner Hangendschichten in Beziehung zur Ausdehnung des letzten Inlandeises. Zs. deutsch. geol. Ges., Berlin, 73, Monatsber., pp. 251–260.

——— and GRAHMANN, R. 1928. Nochmals die Deckschichten des Rabutzer Beckentones. Zs. deutsch. geol. Ges., Berlin, 80, Monatsber., pp. 102–107.

KROKOS, W. 1927. Materijali do charkteristi četwertinnich pokladiw schidnoi ta piwdennoi Ukraini. [Materials concerning the study of the soils of the Ukraine.] Materijali doslidzennja gruntiw Ukraini, Charkow, 5, 326 pp. (Ukrainian with German summary.)

——— 1929. Stratigraphie du Paléolithique supérieur du village de Žuravka du Département de Pryluka. Antropologija, Kijew, 1928, pp. 135–139. (Ukrainian with French summary.)

——— 1930. Stratigrafija gorišnogo paleolitu s. Dowginičiw na Owruččini. [Stratigraphy of the upper Palæolithic of the village of Dowginiči in Volhynia.] Mém. Cl. Sci. nat. techn. Acad. Sci. Ukraine, Kijew, livr. 1–2, no. 10, pp. 27–35. (Ukrainian with German summary.)

——— 1935. Zur Nomenklatur der Quartärablagerungen der Ukraine. C.R. Acad. Sci. USSR, Leningrad-Moscow, 2, pp. 501–506.

LADRIÈRE, M. 1891. Étude stratigraphique du Terrain quaternaire du Nord de la France. Deuxième Partie. Ann. Soc. géol. Nord, Lille, 18, pp. 205–276.

LAMOTHE, L. DE. 1918 [Dec. 21]. Les anciennes nappes alluviales et lignes de Rivage du bassin de la Somme et leurs rapports avec celles de la Méditerranée occidentale. Bull. Soc. géol. France, Paris, (4) 18, pp. 3–58.

LINSTOW, O. v. 1906. Über die Ausdehnung der letzten Vereisung in Mitteldeutschland. Jahrb. Preuss. geol. Landesanstalt, Berlin, 26, pp. 484–494, pl. 12.

MILTHERS, V. 1934. See II, p. 283.

MORDZIOL, C. 1928. Flussterrassen und Löss am Mittelrhein. Festschr. 75jähr. Bestehen naturw. Ver. Coblenz, pp. 23–56.

MÜLLER, K. 1938. Der Stand der Diluvialforschung im Mittelrheingebiet. Mitt. geogr. Ges. München, 31, pp. 180–212.

NAUMANN, E., and PICARD, E. 1915. Die Terrassen des mittleren Saalelaufes. Jahrb. Preuss. geol. Landesanstalt, Berlin, 36 (1), pp. 401–415, pl. 22.

NEEB, E. 1924. Eine paläolithische Freilandstation bei Mainz. Prähist. Zs., Leipzig, 15.

NEUMANN, G. K. L. 1934. Geomorphologische Studien in der Oberlausitz. Mitt. Ver. Erdkunde, Dresden, (N.F.) 1933–34, pp. 1–140, 4 pls., 1 map.

PETERS, E. 1930. Die altsteinzeitliche Kulturstätte Petersfels. 75 pp., 27 pls. Augsburg.

——— and TOEPFER, V. 1932. Der Abschluss der Grabungen am Petersfels bei Engen im badischen Hegau. Prähist. Zs., Leipzig, 23, pp. 155–199, pls. 1, 2.

PONTIER, G. 1910. Remarques sur les faunes d'Abbeville. Ann. Soc. géol. Nord, Lille, 39, pp. 293–303.

——— 1928. Les éléphants fossiles d'Abbeville. Ann. Soc. géol. Nord, Lille, 53, pp. 20–46, pls. 2–5.

RÜGER, L. 1931. Ein Lebensbild von Mauer. Bad. geol. Abh., Karlsruhe, 3, pp. 121–136.

Scherf, E. 1936. Versuch einer Einteilung des ungarischen Pleistozäns auf moderner polyglazialistischer Grundlage. Verh. III. int. Quart.-Konf. Wien, Sept., 1936, pp. 237–247.

Schmidt, R. R., and Wernert, P. 1909. Die archäologischen Einschlüsse der Lösstation Achenheim i. Elsass und die paläolithischen Kulturen des Rheintallösses. Prähist. Zs., Leipzig, **1**, pp. 339–346.

Schmidtgen, O. 1930. Der Aurignac-Mensch bei Mainz. Umschau, Frankfurt a. M., pp. 1–5.

——— and Wagner, W. 1929. Eine altpaläolithische Jagdstelle bei Wallertheim in Rheinhessen. Notizbl. Ver. Erdkunde und Hess. geol. Landesanstalt, Darmstadt, (5) **11**, pp. 1–31, pls. 3–15.

Selzer, G. 1936. Die Gliederung des Lösses im westlichen Eichsfeld und im Talgebiet der oberen Leine. Stille-Festschrift, Stuttgart, pp. 212–222.

Siegert, L. 1909. Bericht über die Begehungen der diluvialen Ablagerungen an der Saale im Anschluss an die Konferenz der Direktoren der Deutschen geologischen Landesanstalten im Jahre 1908. Jahrb. Preuss. geol. Landesanstalt, Berlin, **30** (2), pp. 1–46, pl. 1.

——— 1921. Beiträge zur Kenntnis des Pliocäns und der diluvialen Terrassen im Flussgebiet der Weser. Abh. Preuss. geol. Landesanstalt, Berlin, (n.s.) **90**, 132 pp., 17 pls.

——— and Weissermel, W. 1906. Die Gliederung des Diluviums zwischen Halle und Weissenfels. Prot. deutsch. geol. Ges., Berlin, 1906, pp. 32–49, pl. 7.

——— ——— 1911. Das Diluvium zwischen Halle a. S. und Weissenfels. Abh. Preuss. geol. Landesanstalt, Berlin, (n.f.) **60**, 351 pp., 17 pls.

Soergel, W. 1919. Lösse, Eiszeiten und paläolithische Kulturen. 177 pp., 1 pl. Jena.

——— 1920. Der Rabutzer Beckenton. Veröff. Prov. Mus. Halle, **1** (4).

——— 1924. Die diluvialen Terrassen der Ilm und ihre Bedeutung für die Gliederung des Eiszeitalters. 79 pp. Jena.

——— 1925. Die Gliederung und absolute Zeitrechnung des Eiszeitalters. Fortschr. Geol. Palæont., Berlin, **13**, pp. 125–251, 3 pls.

——— 1926*a*. Excursion ins Travertingebiet von Ehringsdorf. Palæont. Zs., Berlin, **8**, pp. 7–33.

——— 1926*b*. Das Alter der paläolithischen Fundstätten von Taubach-Ehringsdorf-Weimar. Mannus, Leipzig, **18**, pp. 1–13.

——— 1927. Zur Talentwicklung des Werra-Weser- und des Ilm-Saalesystems. Geol. Rundsch., Berlin, **18**, pp. 103–120.

——— 1928. Das geologische Alter des *Homo heidelbergensis*. Palæont. Zs., Berlin, **10**, pp. 217–233.

——— 1929. Das Alter der Sauerwasserkalke von Canstatt. Jber. Mitt. oberrhein. geol. Ver., Stuttgart, 1929, pp. 93–153, pl. 1, 2.

——— 1933. Die geologische Entwicklung der Neckarschlinge von Mauer. Palæont. Zs., Berlin, **15**, pp. 322–341.

——— 1939. Das diluviale System. Fortschr. Geol. Palæont., Berlin, (12) **39**, pp. 155–292.

Stark, P., and Overbeck, F. 1932. Eine diluviale Flora von Johnsbach bei Wartha (Schlesien). Planta, Berlin, **17**, pp. 437–452.

Steinmann, H. G. 1926. Das Diluvium des Niederrheins und die Gliederung des Eiszeitalters. Geol. Rundsch., Berlin, **17**, pp. 436–441.

Toepfer, V. 1933. Die glazialen und präglazialen Schotterterrassen im mittleren Saaletal. Ber. naturf. Ges. Freiburg i. Br., **32**, pp. 1–110.

Weber, C. 1917. Die Pflanzenwelt des Rabutzer Beckentons und ihre Entwicklung unter Bezugnahme auf Klima und geologische Vorgänge. Engler's botan. Jahrb., Leipzig, **54**, Beibl. 120, 50 pp.

Weissermel, W., and Picard, E. 1926. Die Deckschichten des Rabutzer Beckentons. Zs. deutsch. geol. Ges., Berlin, **78**, Monatsber., pp. 141–150.

WEISSERMEL, W., and PICARD, E. 1929. Nochmals die Deckschichten des Rabutzer Beckentons. Zs. deutsch. geol. Ges., Berlin, **81**, pp. 410–414.

WERNERT, P. 1929. La caractérisation faunistique du loess ancien. C.R. XIVe Congr. géol. int., Madrid, 1926, pp. 1975–1987.

——— 1934. Massacres de Cervidés du paléolithique ancien du Castillo (Santander) et d'Achenheim (Bas-Rhin). Ann. Cuerpo Facult. Archiveros Bibliotecarios Arqueólogos, Madrid, **2**, 15 pp., pls. 1–4.

——— 1936. De quelques phénomènes géologiques dans les coupes de la station paléolithique d'Achenheim (Bas-Rhin). Bull. Soc. préhist. franç., Le Mans, 1936 (11), 4 pp.

WÜST, E. 1911. Einige Bemerkungen über Saaleablagerungen zwischen Halle a.S. und Lettin. Centralbl. Min., etc., Stuttgart, 1911, pp. 48–54.

ZEUNER, F. E. 1928. Diluvialstratigraphie und Diluvialtektonik im Gebiet der Glatzer Neisse. 72 pp. Borna-Leipzig.

——— 1929*a*. Eine altdiluviale Flora von Johnsbach bei Wartha. Centralbl. Min., etc., Stuttgart, (B), pp. 179–181.

——— 1929*b*. Der Einfluss der postglazialen Klimaschwankungen auf die Verbreitung von *Ephippigera vitium* Serv. Mitt. zool. Mus., Berlin, **15**, pp. 87–106.

——— 1936. Die Beziehungen des englischen und französischen Pleistozäns zum deutschen Diluvium. Verh. III. Quart.-Konf. Wien, Sept., 1936, pp. 137–138.

——— 1937*a*. See I, p. 281.

——— 1937*b*. A comparison of the Pleistocene of East Anglia with that of Germany. Proc. prehist. Soc., London, (N.S.) **3**, pp. 136–157.

——— 1938. See II, p. 284.

CHAPTER IV

ARMSTRONG, A. L. 1931. Excavations in the Pin Hole Cave, Creswell Crags, Derbyshire. Proc. prehist. Soc., East Anglia, **6**, pp. 330–334.

BADEN-POWELL, D. F. W., 1933. Raised Beaches in Gower. Geol. Mag., London, **70**, p. 239.

——— and REID MOIR, J. R. 1942. On a New Palæolithic Industry from the Norfolk Coast. Geol. Mag., London, **79**, pp. 209–219.

BARROW, G. 1918. Excursion to Chorley Wood. Proc. Geol. Assoc., London, **29**, pp. 140–148.

——— 1919. Some Future Work for the Geologists' Association. Proc. Geol. Assoc., London, **30**, pp. 1–48, pls. 1, 2.

BISAT, W. S. 1940. Older and Newer Drift in East Yorkshire. Proc. Yorks. geol. Soc., Wakefield, **24**, pp. 137–151, pls. 16, 17.

BOSWELL, P. G. H. 1914. On the Occurrence of the North Sea Drift (Lower Glacial), and Certain other Brick-Earths, in Suffolk. Proc. Geol. Assoc., London, **25**, pp. 121–153, pls. 23, 24.

——— 1923. The Geology of the Country around Cromer and Norwich. Proc. Geol. Assoc., London, **34**, pp. 207–222.

——— 1931. The Stratigraphy of the Glacial Deposits of East Anglia in Relation to Early Man. Proc. Geol. Assoc., London, **42**, pp. 87–111.

——— 1936. Problems of the Borderland of Archæology and Geology in Britain. Proc. prehist. Soc., London, (N.S.) **2**, pp. 149–160.

——— 1940. Climates of the Past: A Review of the Geological Evidence. Quart. J. R. meteor. Soc., London, **66**, pp. 249–274.

BROWN, J. A. 1886. The Thames Valley Surface-deposits of the Ealing District and their Associated Palæolithic Floors. Quart. J. geol. Soc., London, **42**, pp. 192–200.

BULL, A. J. 1941. Pleistocene Chronology. Proc. Geol. Assoc., London, **53**, pp. 1–45, pl. 1.

BURCHELL, J. P. T. 1933. The Northfleet 50-foot Submergence later than the Coombe Rock of post-Early Mousterian times. Archæologia, London, **83**, pp. 67–92, pls. 20, 21.

——— 1934*a*. The Middle Mousterian Culture and its relation to the Coombe Rock of Post-Early Mousterian Times. Antiqu. J., London, **14**, pp. 33–39.

——— 1934*b*. Fresh Fact relating to the Boyn Hill Terrace of the Lower Thames Valley. Antiqu. J., London, **14**, pp. 163–166, pl. 20.

——— 1935*a*. Evidence of a Further Glacial Episode within the Valley of the Lower Thames. Geol. Mag., London, 72, pp. 90–91.

——— 1935*b*. Some Pleistocene Deposits at Kirmington and Crayford. Geol. Mag., London, 72, pp. 327–331.

——— 1936*a*. Evidence of a Late Glacial Episode within the Valley of the Lower Thames. Geol. Mag., London, **73**, pp. 91–92.

——— 1936*b*. A Final Note on the Ebbsfleet Channel Series. Geol. Mag., London, **73**, pp. 550–554.

BUSK, G. 1872. On the Animal Remains found by Colonel Lane Fox in the High- and Low-Terrace Gravels at Acton and Turnham Green. Quart. J. geol. Soc., London, **28**, pp. 465–470, pl. 29.

CHANDLER, R. H., and LEACH, A. L. 1912. On the Dartford Heath Gravel and on the Palæolithic Implement Factory. Proc. Geol. Assoc., London, **23**, pp. 102–111.

CHARLESWORTH, J. K. 1928. The Glacial Retreat from Central and Southern Ireland. Quart. J. geol. Soc., London, **84**, pp. 293–343, pls. 23, 24.

——— 1929. The South Wales End-Moraine. Quart. J. geol. Soc., London, pp. 335–358, pl. 20.

CHATWIN, C. P. 1937. East Anglia and adjoining Areas. Geol. Surv. U.K., British Regional Geology, 91 pp., 8 pls.

COOK, W. H. 1923. A Geological Excursion . . . to the Pleistocene Drifts at Aylesford. South-east. Naturalist, London, pp. lxvi–lxxi, 1 pl.

——— and KILLICK, J. R. 1924. On the Discovery of a Flint-working Site of Palæolithic Date in the Medway Valley at Rochester, Kent, with Notes on the Drift-Stages of the Medway. Proc. prehist. Soc. East Anglia, **4**, pp. 133–154, pls. A–D.

DALY, R. A. 1925. Pleistocene Changes of Level. Amer. J. Sci., New Haven, (5) **10**, pp. 281–313.

DEWEY, H. 1913. The Raised Beach of North Devon. Geol. Mag., London, (5) **10**, pp. 154–163.

——— 1932. The Palæolithic Deposits of the Lower Thames Valley. Quart J. geol. Soc., London, **88**, pp. 35–56.

FOX, A. LANE. 1872. On the Discovery of Palæolithic Implements in Association with *Elephas primigenius* in the Gravels of the Thames Valley at Acton. Quart. J. geol. Soc., London, **28**, pp. 449–465.

GEIKIE, J. 1881. Prehistoric Europe. 592 pp., 2 pls. London.

GEOLOGICAL SURVEY OF BRITAIN AND WALES. Quarter-inch, one-inch, and six-inch maps, sheet and district memoirs.

GEORGE, T. N. 1932. The Quaternary Beaches of Gower. Proc. Geol. Assoc., London, **43**, pp. 291–324, pls. 19–21.

——— 1933. The Glacial Deposits of Gower. Geol. Mag., London, **70**, pp. 208–232, pl. 15.

GREEN, J. F. N. 1936. The Terraces of Southernmost England. Quart. J. geol. Soc., London, **92**, pp. lviii–lxxxviii.

HARMER, F. W. 1867. On a third Boulder Clay in Norfolk. Quart. J. geol. Soc., London, **23**, pp. 87–90.

——— and WOOD, S. V., JR. 1869. On a Peculiar Instance of Interglacial Erosion near Norwich. Quart. J. geol. Soc., London, **25**, pp. 259–260, 445–449.

——— 1902. The Later Tertiary History of East Anglia. Proc. Geol. Assoc., London, **17**, pp. 416–479.

HARMER, F. W. 1910. The Pleistocene Period in the Eastern Counties of England. Geology in the Field (Geol. Assoc. Jub. Vol., London), pp. 103–123, pl. 4.

——— 1914–1925. The Pliocene Mollusca of Great Britain. Mon. palæontogr. Soc., London, 2 vols.

——— 1928. The Distribution of Erratics and Drift. Proc. Yorks. geol. Soc., Wakefield, (N.S.) 21, pp. 79–150, pl. 5.

HARRISON, K. 1937. Solar Radiation and the Ice Age in Britain. North-West. Naturalist, Arbroath, 12, pp. 235–251, pl. 11.

HICKS, H. 1892. On the Discovery of Mammoth and other Remains in Endsleigh Gardens, Gordon Street, Gordon Square, and Tavistock Square. Quart. J. geol. Soc., London, 48, pp. 453–468.

HINTON, M. A. C., and KENNARD, A. S. 1905. The relative ages of the stone implements of the lower Thames valley. Proc. Geol. Assoc., London, 19, pp. 76–100, pl. 1.

HINTON, M. A. C. 1910. A Preliminary Account of the British Fossil Voles and Lemmings; with some Remarks on the Pleistocene Climate and Geography. Proc. Geol. Assoc., London, 21, pp. 489–507.

HOLMES, T. V. 1892. The New Railway from Grays Thurrock to Romford: Sections between Upminster and Romford. Quart. J. geol. Soc., London, 48, pp. 365–372.

KENNARD, A. S. 1916. The Pleistocene Succession in England. Proc. prehist. Soc., East Anglia, 2, pp. 249–267.

KING, W. B. R., and OAKLEY, K. P. 1936. The Pleistocene Succession in the Lower part of the Thames Valley. Proc. prehist. Soc., London, (N.S.) 2, pp. 52–76.

KIRKALDY, J. F., and BULL, A. J. 1940. The Geomorphology of the Rivers of the southern Weald. Proc. Geol. Assoc., London, 51, pp. 115–150, pls. 7–10.

LAMPLUGH, G. W. 1913. Age of Raised Beaches. Geol. Mag., London, (5) 10, pp. 238–239.

LANKESTER, R. 1912. On the Discovery of a New Type of Flint Implement below the Base of the Red Crag of Suffolk. Phil. Trans. R. Soc., London, (B) 202, pp. 283–336.

LEACH, A. L. 1911. On the Relation of the Glacial Drift to the Raised Beach near Porth Clais, St. David's. Geol. Mag., London, (5) 8, pp. 462–466.

LEESON, J. R., and LAFFAN, G. B. 1894. On the Geology of the Pleistocene Deposits in the Valley of the Thames at Twickenham, etc. Quart. J. geol. Soc., London, 50, pp. 453–462.

MCCLINTOCK, P. 1933. Interglacial soils and the drift sheets of eastern England. Rep. XVIth int. geol. Congr. Washington, pp. 1041–1053, pl. 1.

MARSTON, A. T. 1938. The Swanscombe Skull. J. R. anthrop. Inst., London, 67, pp. 339–406, 6 pls.

MOIR, J. R. 1920. The Geological Age of the Earliest Palæolithic Flint Implements. Geol. Mag., London, 57, pp. 221–224.

MOVIUS, H. L., Jr. 1942. The Irish Stone Age. 339 pp., 7 pls. Cambridge.

NEWTON, E. T. 1882. The Vertebrata of the Forest Bed Series of Norfolk and Suffolk. Mem. geol. Surv. Engl. Wales, 143 pp., 19 pls.

OAKLEY, K. P., and LEAKEY, M. 1937. Report on Excavations at Jaywick Sands, Essex (1934), with some observations on the Clactonian Industry and on the Fauna and Geological Significance of the Clacton Channel. Proc. prehist. Soc., London, (N.S.) 3, pp. 217–260.

REID, C. 1882. Geology of the Country around Cromer. Mem. geol. Surv. Engl. Wales, Sheet 68E, 143 pp., 1 pl.

——— 1890. The Pliocene Deposits of Britain. Mem. geol. Surv. Engl. Wales, 326 pp., 5 pls.

——— 1916. The Plants of the Late Glacial Deposits of the Lea Valley. Quart. J. geol. Soc., London, 71, pp. 155–163, pl. 15.

SANDFORD, K. S. 1924. The River-Gravels of the Oxford District. Quart. J. geol. Soc., London, 80, pp. 113–179, pl. 9.

SANDFORD, K. S. 1925. The Fossil Elephants of the Upper Thames Basin. Quart. J. geol. Soc., London, **81**, pp. 62–86, pls. 3–6.

——— 1929. The Erratic Rocks and the Age of the Southern Limit of Glaciation in the Oxford District. Quart. J. geol. Soc., London, **85**, pp. 359–388.

——— 1932. Some Recent Contributions to the Pleistocene Succession in England. Geol. Mag., London, **69**, pp. 1–18.

SANER, B. R., and WOOLDRIDGE, S. W. 1929. River-Development in Essex. Essex Naturalist, Buckhurst Hill, **22** (5), pp. 244–250.

SHERLOCK, R. L. 1924. The Superficial Deposits of South Buckinghamshire and South Hertfordshire and the Old Course of the Thames. Proc. Geol. Assoc., London, **35**, pp. 1–28, pls. 1, 2.

——— and NOBLE, H. 1912. On the Glacial Origin of the Clay-with-Flints of Buckinghamshire and on a former Course of the Thames. Quart. J. geol. Soc., London, **68**, pp. 199–212, pls. 12–14.

SMITH, REGINALD A. 1911. A Palæolithic Industry at Northfleet, Kent. Archæologia, London, **62**, pp. 515–532.

SMITH, WORTHINGTON G. 1894. Man the Primeval Savage. 349 pp. London.

SOLOMON, J. D. 1932. The Glacial Succession on the North Norfolk Coast. Proc. Geol. Assoc., London, **43**, pp. 241–271, pl. 13.

STOPES, C. 1904. Palæolithic Implements from the Shelly Gravel Pit at Swanscombe, Kent. Rep. Brit. Assoc. Adv. Sci., London, **73**, pp. 803–804.

(SWANSCOMBE COMMITTEE.) 1938. Report on the Swanscombe Skull. J. R. anthrop. Inst., London, **68**, pp. 17–98, pls. 1–6.

TOMLINSON, M. E. 1929. The Drifts of the Stour-Evenlode Watershed and their Extension into the Valleys of the Warwickshire Stour and Upper Evenlode. Proc. Birmingham nat. Hist. phil. Soc., **15**, pp. 157–196, pl. 6.

——— 1935. The superficial deposits of the Country North of Stratford on Avon. Quart. J. geol. Soc., London, **91**, pp. 423–462, pls. 27–28.

——— 1940. Pleistocene gravels of the Cotswold sub-edge plain from Mickleton to the Frome Valley. Quart. J. geol. Soc., London, **96**, pp. 385–421, pls. 21, 22.

TYLOR, A. 1869. On Quaternary Gravels. Quart. J. geol. Soc., London, **25**, pp. 57–100, pls. 4–9.

WARREN, S. H. 1912. A Late Glacial Stage in the Lea Valley subsequent to the Epoch of River-Drift Man. Quart. J. geol. Soc., London, **68**, pp. 213–251, pls. 15–17.

——— 1914. Report of an Excursion to Edmonton. Proc. Geol. Assoc., London, **25**, pp. 285–287.

——— 1916. The Late-Glacial Stage of the Lea Valley. Quart. J. geol. Soc., London, **71**, pp. 164–182, pl. 16.

——— 1923. The Late-Glacial Stage of the Lea Valley (Third Report). Quart. J. geol. Soc., London, **79**, pp. 603–605.

WILLS, L. J. 1937. The Pleistocene History of the West Midlands. Rep. Brit. Assoc. Adv. Sci., London, 1937, pp. 71–94.

WOOD, S. V. 1848–1882. A Monograph of the Crag Mollusca. Mon. palæontogr. Soc., London, 4 vols.

WOOD, S. V., Jr., and ROME, J. L. 1868. On the Glacial and Post-glacial Structure of Lincolnshire and South-east Yorkshire. Quart. J. geol. Soc., London, **24**, pp. 146–184.

——— and HARMER, F. W. 1872–1874. Supplement to the Monograph of the Crag Mollusca. With an Introductory Outline of the Geology of the same District. Mon. palæontogr. Soc., London, Mon. Crag Mollusca, **3**, 31 + 99 pp., 7 pls.

——— ——— 1877. Later Tertiary Geology of East Anglia. Quart. J. geol. Soc., London, **33**, pp. 74–119.

WOODWARD, H. B. 1881. The Geology of the Country around Norwich. Mem. geol. Surv. Engl. Wales, Sheets 66 N.E. and 66 S.E. 215 pp., 8 pls.

WOODWARD, H. B. 1885. The Glacial Drifts of Norfolk. Proc. Geol. Assoc., London, 9, pp. 111–129.

——— 1909. The Geology of the London District. Mem. geol. Surv. Engl. Wales, 142 pp., 1 map.

WOOLDRIDGE, S. W. 1927*a*. The Pliocene Period in Western Essex and the Pre-Glacial Topography of the District. Essex Naturalist, Buckhurst Hill, 21 (6), pp. 247–268.

——— 1927*b*. The Pliocene History of the London Basin. Proc. Geol. Assoc., London, 38, pp. 49–132.

——— 1928. The 200-foot Platform in the London Basin. Proc. Geol. Assoc., London, 39, pp. 1–26, pl. 1.

——— 1938. The Glaciation of the London Basin and the Evolution of the Lower Thames Drainage System. Quart. J. geol. Soc., London, 94, pp. 627–667.

WRIGHT, W. B. 1914. The Quaternary Ice Age. 464 pp., 18 pls., 5 maps. London.

——— 1937. The Quaternary Ice Age. 2nd ed., 478 pp., 23 pls. London.

——— 1939. Tools and the Man. 236 pp. London.

ZEUNER, F. E. 1936. See III, p. 288.

——— 1937. A Comparison of the Pleistocene of East Anglia with that of Germany. Proc. prehist. Soc., London, (N.S.) 3, pp. 136–157.

CHAPTER V

ADHÉMAR, J. 1842. Révolutions de la mer, déluges périodiques. (2nd edition, 359 pp., 8 pls., 1860.) Paris.

AHLMANN, H. W. 1924. Le niveau de glaciation comme fonction de l'accumulation d'humidité sous forme solide. Geogr. Annaler, Stockholm, 6, pp. 223–272, pl. 4.

ÅNGSTRÖM, A. 1925. The albedo of various surfaces of ground. Geogr. Annaler, Stockholm, 7, pp. 323–342.

BALL, R. 1892. The Cause of an Ice Age. 2nd ed., 180 pp. London.

BAULIG, H. 1935. The Changing Sea Level. Publ. Inst. Brit. Geogr., London, 3, 46 pp.

BAUSCHINGER, T. 1920. Bestimmung und Zusammenhang der astronomischen Konstanten. Encycl. math. Wiss., Leipzig, 2 (2), pp. 844–895.

BECK, P. [1937–] 1938. Studien über das Quartärklima im Lichte astronomischer Berechnungen. Ecl. geol. Helv., Basle, 30, pp. 241–262 ; 31, pp. 137–172, pl. 6.

BLANC, A. C. 1937. Le variazioni delle linee di riva del Mar Caspio, del Mar Nero e del Mediterraneo durante il Quaternario. Boll. Soc. geol. Ital., Roma, 56, pp. 346–366.

BONACINA, L. C. W. 1938. Drift Problems suggested by severe snowstorms in the British Isles with special reference to the permanent Scottish snow-fields. Bull. int. Assoc. Hydrol., Paris, 23, pp. 91–110.

BROOKS, C. E. P. 1926. Climate through the Ages. 439 pp. London.

——— 1927. The mean cloudiness over the earth. Mem. R. meteor. Soc., London, 1 (10), pp. 127–138.

BUCHER, W. H. 1933. The Deformation of the Earth's Crust. 518 pp. Princeton.

CROLL, J. 1875. Climate and Time in their Geological Relations: A Theory of Secular Changes of the Earth's Climate. 577 pp., 7 pls. London.

——— 1885. Discussions on Climate and Cosmology. 327 pp. Edinburgh.

CULVERWELL, E. P. 1894. A mode of Calculating a limit to the Direct Terrestrial Temperatures, etc. Phil. Mag., London, 38, pp. 541–552.

DARWIN, C. R. 1889. On the Structure and Distribution of Coral Reefs. 3rd ed., 344 pp., 2 pls., 1 map. London.

DRAYSON, A. W. 1871. On the probable Cause, Date, and Duration of the Glacial Epoch of Geology. Quart. J. geol. Soc., London, 27, pp. 232–234.

(DRAYSON, A. W.) 1927. The Ice Age, its Date, Duration and Astronomical Cause. 32 pp. Lewes.

ECKARDT, W. R. 1909. Das Klimaproblem der geologischen Vergangenheit und historischen Gegenwart. 183 pp., 4 maps. Braunschweig.
EKHOLM, N. 1901. On the variations of the climate of the geological and historical past and their causes. Quart. J. R. meteor. Soc., London, **27**, pp. 1–61.
GIGNOUX, M. 1936. Géologie stratigraphique. 2nd éd., 709 pp. Paris.
GRABAU, A. W. 1936. Oscillation or Pulsation. Rep. XVIth int. geol. Congr., Washington, 1933, pp. 539–553.
——— 1940. The Rhythm of the Ages. 561 pp., 25 pls. Peking. (Appeared after this chapter was written.)
HANN, J. 1908. Allgemeine Klimalehre. Handb. Klimatologie, **1**, 3rd ed., 394 pp. Stuttgart.
HARGREAVES, R. 1898. Distribution of Solar Radiation on the Surface of the Earth, and its Dependence on Astronomical Elements. Trans. Cambridge phil. Soc., **16** (3), pp. 58–94.
HESS, H. 1904. Die Gletscher. 426 pp., 8 pls., 4 maps. Braunschweig.
HOLMES, A. 1926. Contributions to the Theory of Magmatic Cycles. Geol. Mag., London, **63**, pp. 306–329.
——— 1937. The Age of the Earth. 2nd ed., 263 pp. London.
HUNTINGTON, E., and VISHER, S. S. 1922. Climatic Changes, their Nature and Cause. 329 pp. New Haven.
KERNER-MARILAUN, F. v. 1930. Paläoklimatologie. 512 pp. Berlin.
KLUTE, F. 1928. Die Bedeutung der Depression der Schneegrenze für die eiszeitlichen Probleme. Zs. Gletscherkunde, Berlin, **16**, pp. 70–93.
KÖPPEN, W., and WEGENER, A. 1924. Die Klimate der geologischen Vorzeit. 256 pp., 1 pl. Berlin.
KÖPPEN, W. 1930. Neueres über Verlauf und Ursache des europäischen Eiszeitalters. Gerl. Beitr. Geophys., Leipzig, **26**, pp. 365–394.
——— 1931. Grundriss der Klimakunde. 2nd ed., 388 pp., 9 pls. Berlin and Leipzig.
——— 1933. Die Änderungen der Temperatur in Europa seit der letzten Eiszeit. Meteor. Zs., Braunschweig, **50**, pp. 281–284.
——— 1934. Der Umschwung der Windverhältnisse von Europa vor etwa 12,000 Jahren. Meteor. Zs., Braunschweig, **51**, p. 189.
——— 1935. Vergleich zweier Eiszeiten-Theorien. Gerl. Beitr. Geophys., Leipzig, **43**, pp. 379–387.
KORN, H. 1938. Schichtung und absolute Zeit. N. Jahrb. Min., etc., Stuttgart, B.-Bd. **74***A*, pp. 50–186, 5 + 17 pls.
LAGRANGE, J. L. [1781–] 1782. Théorie des variations séculaires des éléments des planètes. Neue Denkschr. Akad. Wiss., Berlin. Re-publ. in: Œuvres de Lagrange, ed. by J. A. Serret, **5**. I. pp. 125–207; II. pp. 211–344; Paris, 1870.
LEVERRIER, V. J. 1843. Recherches sur l'orbite de Mercure et sur les perturbations. Détermination de la masse de Vénus et du diamètre du soleil. J. Math. pures appl., Paris, **13**, 87 pp.
——— [1855–] 1856. Recherches astronomiques. Ann. Obs. Imp., Paris, **1**, 519 pp., 1 pl.; **2**, 301 pp., 1 pl.
LONGWELL, C. R., KNOPF, A., and FLINT, R. F. 1939. A Textbook of Geology. I. Physical Geology. 2nd ed., 543 pp. New York.
MILANKOVITCH, M. 1913. O rasporedu sunčeve radijacije na površini zemljie. [On the distribution of solar radiation on the surface of the earth.] Glas Srpske K. Akad. Beograd, **91**, pp. 101–179.
——— 1915. Über die Frage der astronomischen Theorien der Eiszeiten. Bull. Trav. Acad. Sci., Zagreb, 1915. (Not seen.)
——— 1920. Théorie mathématique des phénomènes thermiques produits par la radiation solaire. 339 pp. Paris. (Acad. Yougoslave Sci. Arts, Zagreb.)
——— 1930. Mathematische Klimalehre und astronomische Theorie der Klimaschwankungen. Handb. Klimatol., **1**(A), 176 pp. Berlin.

MILANKOVITCH, M. 1934. Der Mechanismus der Polverlagerungen und die daraus sich ergebenden Polbahnkurven. Gerl. Beitr. Geophys., Leipzig, **42**, pp. 70–97.

——— 1936. Durch ferne Welten und Zeiten. 389 pp. Leipzig.

——— 1937. Ein neues Kapitel der exakten Wissenschaften und dessen Anwendung in den beschreibenden Naturwissenschaften. Publ. math. Univ. Belgrade, **6**, pp. 13–31.

——— 1938*a*. Neue Ergebnisse der astronomischen Theorie der Klimaschwankungen. Bull. Acad. R. Serbe Sci. math. nat., Belgrade, (A)**4**, 41 pp.

——— 1938*b*. Astronomische Mittel zur Erforschung der erdgeschichtlichen Klimate. Handb. Geophys., **9**, pp. 593–698. Berlin.

PASCHINGER, V. 1923. Die Eiszeit ein meteorologischer Zyklus. Zs. Gletscherkunde, Berlin, **13**, pp. 29–65.

PATERSON, T. T. 1941. On a World Correlation of the Pleistocene. Trans. R. Soc. Edinburgh, **60** (2), pp. 373–425.

PENCK, A. 1921. Die Höttinger Breccie und die Inntalterrasse nördlich Innsbruck. Abh. preuss. Akad. Wiss., Berlin, phys-math. Kl., 1920(2).

PILGRIM, L. 1904. Versuch einer rechnerischen Behandlung der Eiszeit. Jahresh. Ver. vat. Naturk. Württ., **60**. (Not seen.)

RUSSELL, B. 1931. The ABC of Relativity. 4th ed., 231 pp. London.

SIMPSON, G. C. 1930. The Climate during the Pleistocene Period. Proc. R. Soc. Edinburgh, **50**, pp. 262–296.

——— 1934. World Climate during the Quaternary Period. Quart. J. R. meteorol. Soc., London, **60**, pp. 425–478.

——— 1938. Ice Ages. Nature, London, **141**, pp. 591–598.

——— 1940. Possible causes of change in climate and their limitations. Proc. Linn. Soc., London, **152**, pp. 190–219.

SÖLCH, J. 1932. Der Rückzug der letzten Vergletscherung. Sitzungsb. Heidelb. Akad. Wiss., math. nat. Kl., 1932 (1), pp. 1–25.

SOLGER, F. 1910. Geologie der Dünen. In: Dünenbuch. 404 pp., 3 pls. Stuttgart.

SPITALER, R. 1921. Das Klima des Eiszeitalters. 138 pp., 1 pl. Prag.

——— 1934. Die Sonnenbestrahlung und die Temperaturen von 60° N. bis 60° S. in der Würmeiszeit bis zur Gegenwart. Gerl. Beitr. Geophys., Leipzig, **41**, pp. 359–369.

STOCKWELL, J. N. 1873. Memoir on the secular variations of the elements of the eight principal planets. Smiths. Contr. Knowl., Washington, **18** (3), 199 pp.

THWAITES, F. T. 1939. Outline of Glacial Geology. 115 pp., 11 pls. Ann Arbor, Michigan.

UMBGROVE, J. H. F. 1939. On Rhythms in the History of the Earth. Geol. Mag., London, **76**, pp. 116–129.

WALLACE, A. R. 1880. Island Life or, the Phenomena and Causes of Insular Faunas and Floras, including a revision and attempted solution of the problem of Geological Climates. 526 pp., 3 pls. London.

WEGENER, A. 1937. La genèse des continents et des océans. 236 pp. Paris.

WOLDSTEDT, P. 1930. Kommen Polverlagerungen als Ursache der diluvialen Eiszeiten in Frage? Sitzungsb. preuss. geol. Landesanstalt, Berlin, **5**, pp. 52–54.

WUNDT, W. 1933. Änderungen der Erdalbedo während der Eiszeit. Meteor. Zs. Braunschweig, **50**, pp. 241–249.

——— 1935. Die astronomische Theorie der Eiszeiten und die auftretenden Sekundärwirkungen. Zs. Gletscherkunde, Berlin, **22**, pp. 46–72.

——— 1938*a*. Die astronomische Theorie der Eiszeiten. Aus der Heimat, Stuttgart, **51**, pp. 257–274.

——— 1938*b*. Das Reflexionsvermögen der Erde zur Eiszeit. Meteor. Zs., Braunschweig, **55**, pp. 81–87.

ZEUNER, F. E. 1935. See II, p. 126.

——— 1937. See I, p. 281.

CHAPTER VI

BECK, P. 1938. Studien über das Quartärklima im Lichte astronomischer Berechnungen. Ecl. geol. Helv., Basle, **31**, pp. 137–172, pl. 6.

EBERL, B. 1930. See II, p. 281.

GAMS, H. 1935. Beiträge zur Microstratigraphie und Paläontologie des Pliozäns und Pleistozäns von Mittel- und Osteuropa und Westsibirien. Ecl. geol. Helv., Basle, **28**, pp. 1–31.

DE GEER, G. 1926. On the Solar Curve as dating the Ice Age, the New York Moraine and Niagara Falls through the Swedish Timescale. Geogr. Ann., Stockholm, 1926 (4), pp. 253–284, 3 pls.

GIGNOUX, M. 1936. See V, p. 293.

GIRMOUNSKY, A. W. 1932. Die Probleme der unteren Grenze des Anthropozoikums und einige andere Frage der Synchronisation der anthropozoischen Ablagerungen. Trans. 2nd int. Conf. Assoc. Study Quat. Per. Europe, Leningrad-Moscow, **1**, pp. 63–79.

GRAHMANN, R. 1928. Über die Ausdehnung der Vereisungen Norddeutschlands und ihre Einordnung in die Strahlungskurve. Ber. math. phys. Kl. Sächs. Akad. Wiss., Leipzig, **80**, pp. 134–163.

HEIM, A. 1894. Geologische Nachlese. No. 2. Über das absolute Alter der Eiszeit. Vierteljahrsschr. naturf. Ges., Zürich, **39**.

HOLMES, A. 1915. Radioactivity and the Measurement of Geological Time. Proc. Geol. Assoc., London, **26**, pp. 289–309.

PENCK, A., and BRÜCKNER, E. 1909. See I, p. 280.

PILGRIM, G. E. 1944. The Lower Limit of the Pleistocene in Europe and Asia. Geol. Mag., London, **81**, pp. 28–38.

RUTTEN, L. M. R. 1927. Voordrachten over de geologie van Nederlandsch Oost-Indië. 839 pp. Groningen.

SOERGEL, W. 1925. Die Gliederung und absolute Zeitrechnung des Eiszeitalters. Fortschr. Geol. Palæont., Berlin, **13**, pp. 125–251, 3 pls.

——— 1937. Die Vereisungskurve. 87 pp., 1 pl. Berlin.

STECK, T. 1892. Die Denudation im Kandergebiet. Jber. geogr. Ges., Bern, **11**, pp. 181–188.

TOEPFER, V. 1933. Die glazialen und präglazialen Schotterterrassen im mittleren Saaletal. Ber. naturf. Ges. Freiburg i. Br., **32**, pp. 1–110, pls. 1, 2.

ZEUNER, F. E. 1935. See II, p. 284.

——— 1938*a*. See II, p. 284.

——— 1938*b*. The Chronology of the Pleistocene Sea-levels. Ann. Mag. nat. Hist., London, (11) **1**, pp. 389–405.

CHAPTER VII

BATE, D. M. A. 1928. Excavation of a Mousterian Rockshelter at Devil's Tower, Gibraltar. The Animal Remains. J. R. anthrop. Inst., London, **58**, pp. 92–113.

——— 1937. See GARROD, 1937.

BLANC, A. C. 1935*a*. Formazioni pleistoceniche nel sottosuolo della Versilia. Proc. verb. Soc. Tosc. Sci. nat., Pisa, **43**, 17 pp.

——— 1935*b*. Delle formazioni quaternarie di Nettuno e loro correlazione con la stratigrafia dell'Agro Pontino. Boll. Soc. geol. ital., Roma, **54**, pp. 109–120.

——— 1936*a*. Sulla stratigrafia quaternaria dell'Agro Pontino e della bassa Versilia. Boll. Soc. geol. ital., Roma, **55** (2), pp. 375–396, pls. 21–24.

——— 1936*b*. La stratigraphie de la plaine côtière de la Bassa Versilia (Italie) et la transgression flandrienne en Méditerranée. Rev. géogr. phys., Paris, **9**, pp. 129–162, pls. 1–5.

——— 1936*c*. Le groupe volcanique latial et ses relations stratigraphiques avec le Quaternaire marin. Rev. géogr. phys., Paris, **9**, pp. 57–75.

BLANC, A. C. 1937*a*. Low levels of the Mediterranean Sea during the Pleistocene Glaciation. Quart. J. geol. Soc., London, **93**, pp. 621–651, pls. 36–38.

——— 1937*b*. Über die Quartärstratigraphie des Agro Pontino und der Bassa Versilia. Verh. III int. Quart.-Konf., Wien, pp. 273–279.

——— 1937*c*. Fauna a Ippopotamo ed industrie paleolitiche nel riempimento delle grotte littoranee del Monte Circeo. R. C. Accad. naz. Lincei, Roma, Cl. Sci. fis. mat. nat., (6*a*) **28**, pp. 88–93.

——— 1937*d*. Cronologia glaciale ed industrie paleolitiche nell'Europa centrale e meridionale. A proposito di una recente memoria di A. Penck. Boll. Com. glaciol. ital., Torino, **17**, 18 pp.

——— 1938. Nuove giacimento paleolitico e mesolitico ai Balzi Rossi (Bàussi Russi) di Grimaldi. R. C. Accad. naz. Lincei, Roma, Cl. Sci. fis. mat. nat., (6*a*) **28** (3–4), 7 pp.

——— 1939*a*. L'uomo fossile del Monte Circeo: Un cranio neandertaliano nella Grotta Guattari a San Felice Circeo. R. C. Accad. naz. Lincei, Roma, Cl. Sci. fis. mat. nat. (6*a*) **29** (5), pp. 205–210, pl. 1.

——— 1939*b*. Un giacimento aurignaziano medio nella Grotta del Fossellone al Monte Circeo. Atti XXVI Riun. Soc. ital. Progr. Sci. Bologna, 7 pp.

BLANC, G. A. 1921. Grotta Romanelli, I. Stratigrafia dei depositi e natura e origine di essi. Arch. Antrop. Etnol., Firenze, **50**, pp. 1–39, pls. 1–7.

——— 1928. Sulla presenza di *Alca impennis* Linn. nella formazione pleistocenica superiore di Grotta Romanelli in Terra d'Otranto. Arch. Antrop. Etnol., Firenze, **58**, pp. 3–24, pls. 1–7.

——— 1930. Grotta Romanelli II. Dati ecologici e palentologici. Arch. Antrop. Etnol., Firenze, **58**, 49 pp., 52 pls.

BOULE, M. 1906. Les Grottes de Grimaldi. Résumés et Conclusions des Études géologiques. Anthrop., Paris, **17**, pp. 257–289.

——— CARTAILHAC, E., VERNEAU, R., and VILLENEUVE, L. DE. [1906–] 1919. Les Grottes de Grimaldi (Baoussé-Roussé), **1**, 362 pp., 40 pls., 3 maps; **2**, 324 pp., 23 pls. Monaco.

——— and VILLENEUVE, L. DE. 1927. La Grotte de l'Observatoire à Monaco. Arch. Inst. Paléont. hum., Paris, (mém.), **1**, 113 pp., 26 pls.

BUXTON, L. H. D. 1928. See Garrod, 1928.

DESPOTT, G. 1915. A List of the Birds of Malta compiled for the University Museum of Natural History. 39 pp. Malta.

FISCHER, P. 1928. See Garrod, 1928.

GARROD, D. A. E., BUXTON, L. H. D., SMITH, G. ELLIOT, and BATE, D. M. A. 1928. Excavation of a Mousterian Rock-shelter at Devil's Tower, Gibraltar. Appendices by R. C. Spiller, M. A. C. Hinton, and Paul Fischer. J. R. anthrop. Inst., London, **58**, pp. 33–113.

GARROD, D. A. E. 1936. A Summary of Seven Seasons' Work at the Wady El-Mughara. Bull. Amer. School prehist. Res., Old Lyme (Conn.), **12**, pp. 125–129, pls. 14–24.

——— and BATE, D. M. A. 1937. The Stone Age of Mount Carmel, I. 240 pp., 55 pls. Oxford.

GRAZIOSI, P. 1937. I Balzi Rossi. Guida delle Caverne preistoriche di Grimaldi presso Ventimiglia. Itiner. stor-tur. Riviera Ponente, 40 pp. Albenga.

HOPWOOD, A. T. 1936. Earth-Movements, Ice Ages, and Faunas. Geol. Mag., London, **73**, pp. 185–188.

——— 1940. Fossil Mammals and Pleistocene correlation. Proc. Geol. Assoc., London, **51**, pp. 79–88. London.

KÖPPEN, W. 1931. See I, p. 280.

McCOWN, T. P., and KEITH, Sir A. 1939. The Stone Age of Mount Carmel, II. 390 pp., 28 pls. Oxford.

MARCHETTI, M., and TONGIORGI, E. 1937. Una torba glaciale del Lago di Massaciuccoli (Versilia). Nuov. Giorn. bot. Ital., Firenze (N.S.), **43**, pp. 872–884.

OBERMAIER, H. 1924. Fossil Man in Spain. 495 pp., 23 pls. New Haven, London.
——— 1935. Lösse und Lössmenschen in Europa. Forsch. Fortschr., Berlin, 11, pp. 71–74.
——— 1937a. Quartärprobleme in Oberitalien und Toscana. Forsch. Fortschr., Berlin, 13 (10), 3 pp.
——— 1937b. Quartärprobleme in Latium und Unteritalien. Forsch. Fortschr., Berlin, 13 (13), 3 pp.
PICARD, L. 1932. Zur Geologie des mittleren Jordantales. Z. deutsch. Palästina Ver., 55, pp. 169–237, pls. 17–24.
——— 1937a. Über Fauna, Flora und Klima des Pleistozäns Palästina-Syriens. Verh. III int. Quart.-Konf. Wien, 1936, 4 pp.
——— 1937b. Inferences on the Problem of the Pleistocene Climate of Palestine and Syria drawn from Flora, Fauna and Stratigraphy. Proc. prehist. Soc., London, pp. 58–70.
RAMSAY, R. G. W. 1923. Guide to the Birds of Europe and North Africa. 355 pp. London.
SMITH, J. 1845. On the Geology of Gibraltar. Quart. J. geol. Soc., London, 2, pp. 41–51.
STASI, P. E., and REGALIA, E. [1904–] 1905. Grotta Romanelli (Castro, Terra d'Otranto). Arch. Antrop. Etnol., Firenze, 34, pp. 17–64, pls. 1–4 ; 35, pp. 113–172, 1 pl.
TONGIORGI, E. 1936. Le variazioni climatiche testimoniate dallo studio paleobotanico della serie fiandriana nella pianura della Bassa Versilia presso il Lago di Massaciuccoli. Nuov. Giorn. bot. Ital., Firenze, 43, 3 pp.
——— 1937. Ricerche sulla vegetazione dell' Etruria marittima. V. Documenti per la storia della vegetazione della Toscana e del Lazio. Nuov. Giorn. bot. Ital., Firenze (N.S.), 43, pp. 785–830, pls. 9–20.
VAUFREY, R. 1928. Le Paléolithique Italien. Arch. Inst. Paléont. hum., Paris, 3, 196 pp., 7 pls.
——— 1939. Paléolithique et Mésolithique palestiniens. Rev. Sci., Paris, nos. 6–7, pp. 390–406.
VERNEAU, R. 1933. Catalogue du Musée d'Anthropologie préhistorique. 195 pp. Monaco.
ZEUNER, F. E. 1938a. See II, p. 284.
——— 1938b. Die Gliederung des Pleistozäns und des Paläolithikums in Palästina. Geol. Rundsch., Stuttgart, 29, pp. 514–517.
——— 1938c. (Chronology of middle and upper Palæolithic especially in the Mediterranean Region.) Symposium on the Middle Palæolithic. Rep. Brit. Assoc. Adv. Sci., London, 108, pp. 472–473.
——— 1939. Schwankungen der Sonnenstrahlung und des Klimas im Mittelmeergebiet während des Quartärs. Geol. Rundsch., Stuttgart, 30 (6), pp. 650–658.
——— 1940. The age of Neanderthal Man, with notes on the Cotte de St. Brelade, Jersey, C.I. London Univ. Inst. Arch. geochron. Tables, 2, 20 pp.

CHAPTER VIII

ARMSTRONG, A. L., JONES, N., and MAUFE, H. B. 1936. The Antiquity of Man in Rhodesia as demonstrated by Stone Implements of the Ancient Zambesi Gravels, South of Victoria Falls. J. R. anthrop. Inst., London, 66, pp. 331–368, pl. 21.
CATON-THOMPSON, G. 1932. The Royal Anthropological Institute's Prehistoric Research Expedition to Kharga Oasis, Egypt. Man, London, 32, pp. 129–135, pl. F.
——— and GARDNER, E. W. 1932. The Prehistoric Geography of Kharga Oasis. Geogr. J., London, 80, pp. 369–409, 10 pls.
——— GARDNER, E. W., and HUZAYYIN, S. A. 1937. Lake Moeris, Re-investigations and some Comments. Bull. Inst. Egypte, Le Caire, 19, pp. 243–303, pls. 1–11.

CATON-THOMPSON, G. 1938. Geology and Archæology of the Hadhramaut, south-west Arabia. Nature, London, **142**, pp. 139–140.

——— and GARDNER, E. W. 1939. Climate, Irrigation, and Early Man in the Hadhramaut. Geogr. J., London, **93**, pp. 18–38, 6 pls.

COOKE, H. B. S., and CLARK, J. D. 1939. New fossil elephant remains from the Victoria Falls, Northern Rhodesia, and a preliminary note on the geology and archæology of the deposit. Trans. R. Soc. S. Afr., Cape Town, **27**, pp. 287–319, pls. 12, 13.

DALY, R. A. 1935. The Changing World of the Ice Age. 2nd ed., 271 pp. New Haven.

GARDNER, E. W. 1932. Some Problems of the Pleistocene Hydrography of Kharga Oasis, Egypt. Geol. Mag., London, **69**, pp. 386–421, pls. 26–31.

——— 1935. The Pleistocene Fauna and Flora of Kharga Oasis, Egypt. Quart. J. geol. Soc., London, **91**, pp. 479–515, pls. 30–34. London.

HOPWOOD, A. T. 1926. Mammalia. In: Geology and Palæontology of the Kaiso Bone Beds. Occas. Pap. geol. Surv. Uganda, Entebbe, **2**, pp. 13–36, pls. 2–4.

——— 1933. Die fossilen Pferde von Oldoway. Wiss. Erg. Oldoway Exp. 1913, Berlin, (N.S.) **4**, pp. 112–136, pl. 7. (This series contains numerous other monographs on the Olduvai fauna.)

HUZAYYIN, S. A. 1937. Egyptian University Scientific Expedition to South-west Arabia. Nature, London, **140**, pp. 513–514.

KENT, P. E. 1941. The Recent History and Pleistocene Deposits of the Plateau North of Lake Eyasi, Tanganyika. Geol. Mag., London, **78**, pp. 173–184.

——— 1942. Pleistocene Climates in Kenya and Abyssinia. Nature, London, **149**, pp. 736–737.

KÖPPEN, W. 1931. See I, p. 280.

LEAKEY, L. S. B. 1931. The Stone Age Cultures of Kenya Colony. 288 pp., 31 pls. Cambridge.

——— 1936. Stone Age Africa. 218 pp., 13 pls. London.

——— RECK, H., BOSWELL, P. G. H., and HOPWOOD, A. T. 1933. The Oldoway Human Skeleton. Nature, London, **131**, p. 397.

LOWE, C. VAN RIET. 1937. See: Söhnge, Visser, and Lowe, 1937.

——— 1938. Early Man and Past Climates in South Africa. S. Afr. J. Sci., Johannesburg, **35**, pp. 432–450.

MACINNES, D. G. 1942. Miocene and Post-Miocene Proboscidea from East Africa. Trans. zool. Soc., London, **25** (2), pp. 33–106, pls. 1–8.

MALAN, B. D. 1943. Some Problems of the Stone Age in South Africa. S. Afr. J. Sci., Johannesburg, **39**, pp. 71–87.

MILANKOVITCH, M. 1938*a*. See V, p. 294.

——— 1938*b*. See V, p. 294.

NILSSON, E. 1940. Ancient Changes of Climate in British East Africa and Abyssinia. Geogr. Ann., Stockholm, **22**, pp. 1–79, pl. 1.

O'BRIEN, T. P. 1939. The Prehistory of Uganda Protectorate. 319 pp., 26 pls. Cambridge.

RECK, H. 1914. Erste vorläufige Mitteilung über den Fund eines Menschenskelets aus Zentralafrika. Sitzungsber. Ges. naturf. Freunde, Berlin, 1914 (3), pp. 81–95, pls. 1–3.

——— (after 1930). Über das Alter der ostafrikanischen Gräben und Bruchstufen. Festschr. Carl Uhlig, Öhringen, 11 pp., pls. 5, 6.

SÖHNGE, P. G., VISSER, D. J. L., and LOWE, C. VAN RIET. 1937. The Geology and Archæology of the Vaal River Basin. Mem. geol. Surv. S. Afr., Pretoria, **35**, 184 pp., 36 pls.

SPITALER, R. 1934. Die Verschiebung der Kalmen in der Vorzeit. Meteor. Zs., Braunschweig, **51**, pp. 206–209.

WAYLAND, E. J. 1934. Rifts, Rivers, Rains and Early Man in Uganda. J. R. anthrop. Inst., London, **64**, pp. 333–352, pls. 43–50.

WAYLAND, E. J. 1939. Outlines of the Physiography of Karamoja in Relation to Erosion and Water Supply. Bull. geol. Surv. Uganda, Entebbe, **3**, pp. 145–153.
WUNDT, W. 1934. Die Lage der Kalmen. Meteor. Zs., Braunschweig., **51**, pp. 49–53.
—— 1937. Die Lage des meteorischen Äquators. Meteor. Zs., Braunschweig, **54**, pp. 224–226.
ZEUNER, F. E. 1938. See VI, p. 295.

CHAPTER IX

BADEN-POWELL, D. F. W. 1928. On the climatic equivalent of Raised Beach mollusca. Rep. Comm. Plioc. Pleist. Terr., Union géogr. int., **1**, pp. 107–111.
—— 1930. Notes on Raised Beach Mollusca from the Isle of Portland. Proc. malacol. Soc., London, **19** (2), pp. 67–76.
BAULIG, H. 1935. The Changing Sea Level. Inst. Brit. Geographers' Publ., London, **3**, 46 pp.
BIGOT, A. 1930. Les terrasses pleistocènes du littoral du Cotentin. Cent. Soc. géol. France, Paris, livre jubilaire, **1**, pp. 133–149, pls. 23, 24.
BLANC, A. C. 1936. See VII, p. 295 (1936*b*).
—— 1937. See VII, p. 296 (1937*a*).
BOULE, M. 1919. See Boule, Cartaillac, Verneau and Villeneuve, see VII, p. 296.
BREUIL, H., VAULTIER, M., and ZBYSZEWSKI, G. 1943. Les plages anciennes portugaises entre les Caps d'Espichel et Carvoeiro et leurs industries paléolithiques. Proc. prehist. Soc., London, (N.S.) **8**, pp. 21–25.
BULLEID, A., and JACKSON, W. 1937. The Burtle Sand Beds of Somerset. Proc. Somersetshire archæol. nat. Hist. Soc., Taunton, **83**, pp. 171–195, pls. 27–33.
CLARKE, E. DE C. 1926. The Geology and Physiography of the Neighbourhood of Perth, Western Australia. Handbook for Western Australia, Australas. Assoc. Adv. Sci., Perth, pp. 23–30.
CLARKE, W. B. 1841. On the Geological Phenomena in the Vicinity of Cape Town, Southern Africa. Proc. geol. Soc., London, **3** (2), pp. 418–423.
COLENETTE, A. 1916. The Pleistocene Period in Guernsey. Trans. Guernsey Soc. nat. Sci., **7**, pp. 337–408, pls. 1–9.
COOKE, C. W. 1930. Correlation of Coastal Terraces. J. Geol., Chicago, **38**, pp. 557–589.
DALY, R. A. 1934. See VIII, p. 298.
DARWIN, C. R. 1846. Geological Observations on South America. Being the third part of the Geology of the Voyage of the "Beagle" . . . during . . . 1832 to 1836. 279 pp., 5 pls., 1 map. London.
DEPÉRET, C. 1906. Les anciennes lignes de rivage de la côte française de la Méditerranée. Bull. Soc. géol. France, Paris (4) **6**, pp. 207–230.
—— 1918 [Mars 25]. Essai de coordination chronologique générale des temps quaternaires. C. R. Acad. Sci., Paris, **167**, pp. 418–422.
—— 1921. La classification du Quaternaire et sa corrélation avec les niveaux préhistoriques. C. R. Soc. géol. France, Paris, 1921, pp. 125–127.
DEWEY, H. 1913. The Raised Beach of North Devon. Geol. Mag., London (5) **10**, p. 154.
—— 1935. South-west England. British Regional Geology (Geol. Survey and Museum, London), 70 pp., 12 pls.
DUBOIS, G. 1924. Recherches sur les terrains quaternaires du Nord de la France. Mém. Soc. géol. Nord, Lille, **8**, pp. 1–356, 5 pls.
FERUGLIO, E. 1933. I Terrazzi marini della Patagonia. Giorn. Geol. Bologna (2) **8** *bis*, pp. 3–288, pls. 1–11.
FOWLER, J. 1932. The "One Hundred Foot" Raised Beach between Arundel and Chichester, Sussex. Quart. J. geol. Soc., London, **88**, pp. 84–99, pls. 8, 9.

GIGNOUX, M. 1913. Les formations marines pliocènes et quaternaires de l'Italie du sud et de la Sicile. Ann. Univ. Lyon, (N.S.) 1 (36), 693 pp.

——— 1936. See V, p. 293.

GODWIN-AUSTEN, R. 1857. On the Newer Tertiary Deposits of the Sussex Coast. Quart. J. geol. Soc., London, 13, pp. 40–72.

GOODWIN, A. J. H., and MALAN, B. D. 1935. Archæology of the Cape St. Blaize Cave and Raised Beach, Mossel Bay. Ann. S. Afr. Mus., Cape Town, 24 (3), pp. 111–140.

GREEN, J. F. N. 1936. The Terraces of southernmost England. Quart. J. geol. Soc., London, 92, pp. lviii–lxxxviii.

——— 1943. The Age of the Raised Beaches of South Britain. Proc. Geol. Assoc., London, 54, pp. 129–140.

HANSON-LOWE, J. 1938. Bearing of Morphological Data in the Channel Islands on the Eustatic Theory. J. Geomorph., New York, 1, pp. 91–103.

HAUGHTON, S. H. 1925. The Tertiary Deposits of the South Eastern Districts of the Cape Province. Trans. geol. Soc. S. Afr., Johannesburg, 28, pp. 27–32.

——— 1932. The Late Tertiary and Recent Deposits of the West Coast of South Africa. Trans. geol. Soc. S. Afr., Johannesburg, 34, pp. 19–57, pls. 4–5.

HOWCHIN, W. 1924. The Recent Extinction of Certain Marine Animals of the Southern Coast of Australia, together with other Facts that are Suggestive of a Change in Climate. Rep. Australas. Assoc. Adv. Sci., Wellington, 16, pp. 94–101.

——— 1929. Geology of South Australia. 2nd ed., 320 pp. Adelaide.

HUE, E. 1928. Contribution à l'étude du Quaternaire. Plage surélevé à Luc-sur-Mer (Calvados). Bull. Soc. préhist. franç., Paris, 25 (10).

HUGHES, T. M. M'KENNY. 1887. On the Ancient Raised Beach and Boulders near Braunton and Croyde, in N. Devon. Quart. J. geol. Soc., London, 43, pp. 657–670, 6 figs.

HUNT, A. R. 1888. The Raised Beach of the Thatcher Rock; its Shells and their Teaching. Trans. Devon. Assoc., Plymouth, 21, pp. 225–253.

ISSEL, A. 1892. Liguria Geologica e Preistorica. Vol. i, 440 pp.; vol. ii, 376 pp.; 38 pp. of explan. of plates, 30 pls., 1 map. Genova.

JOHNSON, D. 1931*a*. The correlation of ancient marine levels. C. R. Congr. int. Géogr., Paris, 2 (1), pp. 42–54.

——— 1931*b*. Supposed two-metre eustatic bench of the pacific shores. C. R. Congr. int. Géogr., Paris, 2 (1), pp. 158–163, pl. 1.

——— 1938. Shore Processes and Shoreline Development. 4th printing, 584 pp., 73 pls. New York.

JONES, O. T. 1924. The Upper Towy Drainage System. Quart. J. geol. Soc., London, 80, pp. 568–609, pls. 43–45.

KRIGE, A. V. 1927. An Examination of the Tertiary and Quaternary Changes of Sea Level in South Africa, with Special Stress on the Evidence in Favour of a Recent World-Wide Sinking of Ocean Level. Ann. Univ. Stellenbosch, 5, pp. 1–81, 5 pls., 1 map.

LAMOTHE, R. DE. 1911. Les anciennes lignes de rivage du Sahel d'Alger et d'une partie de la côte algérienne. Mém. Soc. géol. France, Paris (4) 1 (6), 288 pp., 3 pls., 1 map.

——— 1916. Les anciennes lignes de rivage du bassin de la Somme et leur concordance avec celles de la Méditerranée occidentale. C. R. Acad. Sci., Paris, 162, pp. 948–951.

——— 1918. See III, p. 286.

LAWSON, H. S. 1914. Notes on the Low Level Raised Beach at Portelet Bay. Bull. Soc. Jers., St. Hélier, 7, pp. 456–457.

MARTIN, E. A. 1929. The Pleistocene Cliff-formation of Brighton. South-east. Naturalist, London, 1929, pp. 60–72.

MOLENGRAAFF, G. A. F. 1921. De Geologie der Zeën van Nederlandsch Oost-Indië. De Zeën van Nederlandsch Oost-Indië, pp. 272–357, 7 maps. Leiden.

MOLENGRAAFF, G. A. F. 1930. The coral reefs in the East Indian Archipelago, their distribution and mode of development. Proc. 4th Pac. Sci. Congr., Java, 2, pp. 55–89.

MOURANT, A. E. 1933. The Raised Beaches and Other Terraces of the Channel Islands. Geol. Mag., London, 70, pp. 58–66.

——— 1935. The Pleistocene Deposits of Jersey. Bull. Soc. Jers., St. Hélier, 12, pp. 489–496.

NAISH, T. E. 1919. The Raised Beach at South Hill. Bull. Soc. Jers., St. Hélier, 9 (44), pp. 117–121.

NORDMANN, V. 1928. Position stratigraphique des Dépôts d'Eem. Danm. geol. Undersøg., Copenhagen, (2) 47, 81 pp., 4 pls.

OAKLEY, K. P., and CURWEN, E. C. 1937. The Relation of the Coombe Rock to the 135-ft. Raised Beach at Slindon, Sussex. Proc. Geol. Assoc., London, 48, pp. 317–323, pl. 30.

PALMER, L. S., and COOKE, J. H. 1923. The Pleistocene Deposits of the Portsmouth District and their Relation to Man. Proc. geol. Assoc., London, 34, pp. 253–282.

——— 1930. The Raised Beaches near Portsmouth. South-east. Naturalist, London, pp. 66–75.

PENGELLY, W. 1867. The Raised Beaches in Barnstaple Bay, North Devon. Trans. Devon. Assoc., Plymouth, 2, pp. 43–56.

PRESTWICH, J. 1875. Notes of the Phenomena of the Quaternary Period in the Isle of Portland and around Weymouth. Quart. J. geol. Soc., London, 31, pp. 29–54, pl. 1.

REID, C. 1892. The Pleistocene Deposits of the Sussex Coast, and their Equivalents in Other Districts. Quart. J. Geol. Soc., London, 48, pp. 344–361.

RICHARDS, H. G. 1936. Fauna of the Pleistocene Pamlico Formation of the Southern Atlantic Coastal Plain. Bull. geol. Soc. Amer., New York, 47, pp. 1611–1656, 4 pls.

——— 1937. Marine Pleistocene Mollusks as Indicators of Time and Ecological Conditions. Early Man, pp. 75–84. Philadelphia.

ROGERS, A. W. 1905. A Raised Beach Deposit near Klein Brak River. Ann. Rep. geol. Comm. Cape of Good Hope, Cape Town, 10, pp. 291–296.

SCHWARZ, E. H. L. 1906. The Coast Ledges in the South-West of the Cape Colony. Quart. J. geol. Soc., London, 62, pp. 70–86.

SCRIVENOR, J. B. 1943. Geological and climatic factors affecting the distribution of Life in the [Indo-Australian] Archipelago. Proc. Linn. Soc., London, 154, pp. 120–126.

SEDGWICK, A., and MURCHISON, R. J. 1837. Description of a Raised Beach in Barnstaple Bay, on the North-West Coast of Devonshire. Proc. geol. Soc., London, 2, pp. 441–443.

——— 1840. (Same title.) Trans. geol. Soc., London (2) 5, pp. 279–286.

SHAND, S. J. 1914. The Terraces of Eerste River at Stellenbosch. Trans. geol. Soc. S. Afr., Johannesburg, 16, pp. 147–164, pls. 21, 22.

SHANNON, W. G. 1927. The Petrography and Correlation of the Surface Deposits of South-east Devon. Geol. Mag., London, 64, pp. 145–153.

SINEL, J. 1923. Prehistoric Times and Men of the Channel Islands. 2nd ed., 169 pp., 3 maps, 21 pls. Jersey.

STOW, G. W. 1871. On some Points in South African Geology. Quart. J. geol. Soc., London, 27, pp. 497–548.

TINDALE, N. B. 1933. Tantanoola Caves, South-East of South Australia: Geological and Physiographical Notes. Trans. R. Soc. South Austral., Adelaide, 57, pp. 130–142.

DU TOIT, A. L. 1917. Report on the Phosphates of Saldanha Bay. Mem. geol. Surv. S. Afr., Pretoria, 10, 38 pp., 2 pls.

——— 1922. The Evolution of the South African Coastline. South Afr. geogr. J., Johannesburg, 5, pp. 5–13.

UMBGROVE, J. H. F. 1930. The Amount of Maximal Lowering of the Sea-Level in the Pleistocene. Proc. 4th Pac. Sci. Congr., Java, 1929, 2, pp. 105–113.

USSHER, W. A. E., and LLOYD, W. 1933. The Geology of the Country around Torquay. Mem. geol. Surv. Engl. Wales, sheet 350. 2nd ed., 169 pp., 7 pls.

WHITE, H. J. O. 1924. The Geology of the Country near Brighton and Worthing. Mem. geol. Surv. Engl. Wales, sheets 318 and 333. 144 pp., 4 pls.

ZBYSZEWSKI, G. 1943. La classification du paléolithique ancien et la chronologie du Quaternaire de Portugal en 1942. Bol. Soc. geol. Portugal, 2 (2–3), 111 pp., 1 pl.

ZEUNER, F. E. 1928. See III, p. 288.

——— 1936. See I, p. 281.

——— 1938. See VI, p. 295.

——— 1940*a*. A new Subspecies of Red Deer from the Upper Pleistocene of Jersey, Channel Islands. Ann. Mag. nat. Hist., London, (11) **5**, pp. 326–328.

——— 1940*b*. See VII, p. 297.

——— 1940*c*. *Cervus elaphus jerseyensis*, and other Fauna in the 25-ft. Beach of Belle Hougue Cave, Jersey, C.I. Bull. Soc. Jers., St. Hélier.

——— 1942. Pleistocene Chronology. Proc. Geol. Assoc., London, **53**, pp. 35–37.

——— 1943. Studies in the Systematics of Troides Hübner and its allies. Distribution and Phylogeny in Relation to the Geological History of the Australasian Archipelago. Trans. zool. Soc., London, **25** (3), pp. 107–184.

CHAPTER X

ABBOTT, W. J. L. 1892. The Section exposed in the Foundation of the New Admiralty Offices. Proc. Geol. Assoc., London, **12**, pp. 346–356.

ANDRÉE, J. 1931. Die frühmesolithische Fauna aus dem Hohlen Stein bei Callenhardt. Abh. westf. Prov.-Mus. Naturk., **2**, pp. 1–11.

——— 1939. Der eiszeitliche Mensch in Deutschland und seine Kulturen. 758 pp. Stuttgart.

BÄCHLER, E. 1906. Die prähistorische Kulturstätte in der Wildkirchli-Ebenalphöhle. Verh. Schweiz. nat. Ges., St. Gallen, 1906.

BERNSEN, J. J. A. [1930–] 1934. Eine Revision der fossilen Säugetierfauna aus den Tonen von Tegelen. Natuurh. Maandbl., Limburg, **19–23** (9 parts).

CAMPANA, D. DEL. 1913. I. Cani Pliocenici di Toscana. Palaeont. Ital., Pisa, **19**, pp. 189–254, pl. 13–22.

COMMONT, V. 1910. See III, p. 285 (1910*f*).

DUBOIS, A., and STEHLIN, H. G. [1932–] 1933. La grotte de Cotencher, station moustérienne. Mém. Soc. paléont. Suisse, Bâle, **52**, pp. 1–178, 9 pls. ; **53**, pp. 179–292, pls. 10–15.

GRAHMANN, R. 1935. L'âge géologique de l'industrie paléolithique de Markkleeberg. Anthrop., Paris, **45**, pp. 257–279.

HEIERLI, J. 1907. Das Kesslerloch bei Thaingen. Neue Denkschr. Schweiz. naturf. Ges., **43**.

HINTON, M. A. C. 1926*a*. Monograph of the Voles and Lemmings (Microtinæ), living and extinct. Vol. I, 488 pp., 15 pls. British Museum (Natural History), London.

——— 1926*b*. The Pleistocene Mammalia of the British Isles and their Bearing upon the Date of the Glacial Period. Proc. Yorks. geol. Soc., Wakefield, (N.S.) **20**, pp. 325–348.

HOPWOOD, A. T. 1935. Fossil Elephants and Man. Proc. Geol. Assoc., London, **46**, pp. 46–60.

——— 1937. The former distribution of Caballine and Zebrine horses in Europe and Asia. Proc. zool. Soc., London, 1936, pp. 897–912, pls. 1, 2.

——— 1938. Correlation of Certain Tertiary Deposits of India and Europe. Rec. geol. Surv. India, **73**, pp. 472–479.

——— (with J. REID MOIR). 1939. Excavations at Brundon, Suffolk (1935–37). Proc. prehist. Soc., London, (N.S.) **5**, pp. 1–32.

JAKOBI, A. 1931. Das Rentier. Zool. Anz., Leipzig, **96** (Erg. Bd.), 264 pp., 6 pls.

JOHNSON, J. P. 1901. The Pleistocene Fauna of West Wittering. Proc. Geol. Assoc., London, **17**, pp. 261–264.

KENNARD, A. S. 1935. The Mollusca of the Pleistocene Deposits at Lion Point, Clacton. Essex Naturalist, Buckhurst Hill, **24**, pp. 29–31.

——— and WOODWARD, B. B. 1901. The Post-Pliocene non-marine Mollusca of the south of England. Proc. Geol. Assoc., London, **17**, pp. 213–260.

——— ——— 1922. The Post-Pliocene non-marine Mollusca of the east of England. Proc. Geol. Assoc., London, **33**, pp. 104–142.

KOKEN, E. 1912. Die Geologie und Tierwelt der paläolithischen Kulturstätten Deutschlands. In: Schmidt, R. R., Die Diluviale Vorzeit Deutschlands, pp. 159–228. Stuttgart.

LYDEKKER, R. [1885–] 1887. Catalogue of the Fossil Mammalia in the British Museum. 5 vols. London.

MAJOR, C. J. FORSYTH. 1885. On the Mammalian Fauna of the Val d'Arno. Quart. J. geol. Soc., London, **41**, pp. 1–8.

MILLER, G. S. 1912. Catalogue of the Mammals of Western Europe. 1019 pp. British Museum (Natural History), London.

NEWTON, E. T. 1882. The Vertebrata of the Forest Bed Series of Norfolk and Suffolk. Mem. geol. Surv. Engl. Wales, 143 pp., 19 pls.

NÜESCH, J. 1896. Das Schweizersbild. Neue Denkschr. Schweiz. Ges. Naturwiss., **35**.

OBERMAIER, H. 1924. Fossil Man in Spain. 495 pp., 23 pls. New Haven.

OSBORN, H. F. 1922. Pliocene and Early Pleistocene Mammalia of East Anglia, Great Britain, in Relation to the Appearance of Man. Geol. Mag., London, **59**, pp. 433–441, 1 table.

——— 1942. Proboscidea. Vol. II. Stegodontoidea, Elephantoidea. Pp. 805–1676, pls. 13–30. New York.

PENCK, A., and BRÜCKNER, E. 1909. See I, p. 280.

PETERS, E., and TOEPFER, V. 1932. Der Abschluss der Grabungen am Petersfels bei Engen im badischen Hegau. Prähist. Zs., **23**, pp. 155–199.

PILGRIM, G. E. 1932. The Fossil Carnivora of India. Palæont. Indica, Calcutta, (N.S.) **18**, 232 pp., 10 pls.

PONTIER, G. 1910. See III, p. 286.

——— 1928. See III, p. 286.

REID, C. 1890. The Pliocene Deposits of Britain. Mem. geol. Surv. U.K., 326 pp., 5 pls.

——— 1892. The Pleistocene Deposits of the Sussex Coast, and their Equivalents in Other Districts. Quart. J. geol. Soc., London, **48**, pp. 344–364.

——— 1893. A Fossiliferous Pleistocene Deposit at Stone, on the Hampshire Coast. Quart. J. geol. Soc., London, **49**, pp. 325–329.

RÜGER, L. 1931. Ein Lebensbild von Mauer. Bad. geol. Abh. Karlsruhe, **3**, pp. 121–136.

SAINTY, J. E. 1929. The Problems of the Crag. Proc. prehist. Soc. East Anglia, **6**, pp. 57–75.

SCHAUB, S. 1923. Neue und wenig bekannte Carnivora von Senèze. Ecl. geol. Helv., Basle, **18**, pp. 281–295.

——— 1928. Die Antilopen des Toskanischen Oberpliozäns. Ecl. geol. Helv., Basle, **21**, pp. 260–266.

SCHREUDER, A. 1935. A Note on the Carnivora of the Tegelen Clay, with some Remarks on the Grisoninæ. Arch. Néerl. Zool., Leiden, **2**, pp. 73–94.

——— 1936. Fossil Voles and a Lemmus out of Well-borings in the Netherlands. Verh. Kon. Akad. Wet., Amsterdam, (2) **35**, pp. 1–24.

SOERGEL, W. 1912. *Elephas trogontherii* Pohl. und *Elephas antiquus* Falc., ihre Stammesgeschichte und ihre Bedeutung für die Gliederung des deutschen Diluviums, Palæontogr., Stuttgart, **60**, pp. 1–114, 8 tables, 3 pls.

Soergel, W. 1914. Die diluvialen Säugetiere Badens. Mitt. Bad. geol. Landesanst., Heidelberg, **9**, pp. 1–254, pls. 1–5.

——— 1927. *Cervus megaceros mosbachensis* n. sp. und die Stammesgeschichte der Riesenhirsche. Abh. Senckenb. naturf. Ges. Frankfurt, **41**, pp. 365–408, pls. 17–20.

Stehlin, H. G. 1923. Die oberpliozäne Fauna von Senèze (Haute-Loire). Ecl. geol. Helv., Basle, **18**, pp. 268–281.

——— 1932. See Dubois and Stehlin.

Studer, T. 1904. Die Knochenreste aus der Höhle zum Kesslerloch bei Thaingen. Neue Denkschr. Schweiz. Ges. Naturw., Zürich, **39**, pp. 75–112.

Tesch, P. 1934. De Opeenvolging van de Oud-Plistocene Lagen in Nederland. Tijds. Kon. ned. aardr. Gen., 1934, pp. 649–675.

Toepfer, V. 1934. Ein diluviales Steinbockgehörn aus Thüringen. Palæont. Zs., Berlin, **16**, pp. 267–281.

——— 1935. Die mitteldiluvialen Säugetierreste aus der Saaleterrasse bei Lengefeld-Bad Kösen. N. Jahrb. Min., etc., Stuttgart. B.-Bd. **74B**, pp. 63–88.

Warren, S. H. 1923. The *Elephas-antiquus* Bed of Clacton-on-Sea (Essex) and its Flora and Fauna. Quart. J. geol. Soc., London, **79**, pp. 606–636, 1 table.

Weithofer, K. A. 1890. Die fossilen Proboscidier des Arnothales in Toskana. Beitr. Paläont. Österr. Ung., Wien, **8**, pp. 107–240, 15 pls.

Wüst, E. 1922. Beiträge zur Kenntnis der diluvialen Nashörner Europas. Centralbl. Min., etc., Stuttgart, pp. 641–656, 680–688.

Zeuner, F. E. 1934. Die Beziehungen zwischen Schädelform und Lebensweise bei den rezenten und fossilen Nashörnern. Ber. naturf. Ges. Freiburg i. Br., **34**, pp. 21–80, 8 pls.

——— 1937. See IV, p. 292.

——— 1943. See IX, p. 302.

——— 1944. New Reconstructions of the Mammoth and the Straight-tusked Elephant. Proc. Linn. Soc., Lond., **155**, pp. 245–251.

——— 1945. Dating the Past. London (Methuen). (In the press.)

Zuffardi, P. 1913. Elefanti fossili del Piemonte. Palæontogr. Ital., Pisa, **19**, pp. 121–187, pls. 7–12.

INDEX

NOTE.—For major headings, or subjects discussed at some length, consult CONTENTS, p. v. For terms, geographical notations, genera and species, and authors' names, use INDEX.

Most compound terms are indexed under the defining epithet. For instance, *Faunal break*, see *Faunal*; *Heliocentric length of perihelion*, see *Heliocentric*. Chief reference in *italics*. Where genera and species are mentioned repeatedly in faunal lists on the same page, a small index figure gives the number of references.

THE

RAY SOCIETY.

INSTITUTED 1844.

FOR THE PUBLICATION OF WORKS ON NATURAL HISTORY.

LIST OF RECENT AND FORTHCOMING PUBLICATIONS.

FEBRUARY, 1945.

OFFICERS AND COUNCIL.

1944–45.

President.

SIR SIDNEY F. HARMER, K.B.E., Sc.D., F.R.S., F.L.S., F.Z.S.

Vice-Presidents.

PROF. F. BALFOUR-BROWNE, F.R.S.E., F.L.S.
LT.-COL. R. B. SEYMOUR SEWELL, F.R.S., F.L.S.
E. S. RUSSELL, O.B.E., M.A., D.Sc., F.L.S.

Council.

G. P. BIDDER, Sc.D., F.L.S.
H. R. DARLINGTON, F.L.S.
Capt. CYRIL R. P. DIVER, F.L.S.
R. GURNEY, D.Sc., F.L.S., F.Z.S.
MARTIN A. C. HINTON, F.R.S., F.L.S., F.G.S.
S. W. KEMP, Sc.D., F.R.S.
E. R. MARTIN.
D. M. REID, F.L.S.
E. A. ROBINS, F.L.S.
D. J. SCOURFIELD, I.S.O., F.L.S.
R. S. WILSON SEARS, F.R.M.S.
MALCOLM A. SMITH, M.R.C.S., L.R.C.P., F.L.S.
C. S. TODD.

Treasurer.

F. E. WEISS, D.Sc., F.R.S., F.L.S.

Secretary.

W. T. CALMAN, C.B., LL.D., D.Sc., F.R.S., F.L.S.;
c/o British Museum (Natural History),
Cromwell Road, London, S.W. 7.

ANNUAL SUBSCRIPTION ONE GUINEA.

Members desiring to purchase any of the Society's Publications should apply to the Secretary.

Agents for sale to the public and to the trade:
BERNARD QUARITCH, LTD.,
11, GRAFTON STREET, NEW BOND STREET, LONDON, W. 1.

RECENTLY ISSUED AND FORTHCOMING MONOGRAPHS.

A complete list of the Society's publications will be sent on application.

* indicates that a few copies only remain in stock, for which special application must be made to the Council.

For the Sixty-fourth Year, 1907.

87. The British Marine Annelids. By W. C. McIntosh. Vol. II, Part I. Polychæta. Nephthydidæ to Syllidæ. viii + 232 + 46 pp., 22 plates (xliii–l, lvii–lxx). Folio. 1908. *(25/-)*

For the Sixty-fifth Year, 1908.

88. The British Desmidiaceæ. By W. and G. S. West. Vol. III. xvi + 274 + 62 pp., 31 plates (lxv–xcv). 8vo. 1908. *(25/-)**

89. The British Freshwater Rhizopoda and Heliozoa. By the late James Cash, assisted by John Hopkinson. Vol. II. The Rhizopoda, Part II. xviii + 168 + 32 pp., 16 plates (xvii–xxxii), and frontispiece. 8vo. 1909. *(12/6)*

For the Sixty-sixth Yeor, 1909.

90. The British Nudibranchiate Mollusca. By the late Joshua Alder and the late Albany Hancock. Part 8 (supplementary). Text by Sir Charles Eliot. viii + 198 + 18 pp., 8 plates. Folio. 1910. *(25/-)*

For the Sixty-seventh Year, 1910.

91. The British Marine Annelids. By W. C. McIntosh. Vol. II, Part 2. Polychæta. Syllidæ to Ariciidæ. vii + 292 (233–524) + 46 pp., 23 plates (li–lvi, lxxi–lxxxvii). Folio. 1910. *(25/-)*

For the Sixty-eighth Year, 1911.

92. The British Desmidiaceæ. By W. and G. S. West. Vol. IV. xiv + 194 + 66 pp., 33 plates (xcvi–cxxviii). 8vo. 1912. *(25/-)*

93. The British Tunicata. By the late Joshua Alder and the late Albany Hancock. Edited by John Hopkinson. Vol. III. xii + 114 + 34 pp., 16 plates (li–lxvi), and frontispiece. 8vo. 1912. *(12/6)*

For the Sixty-ninth Year, 1912.

94. A Bibliography of the Tunicata. By John Hopkinson. xii + 288 pp. 8vo. 1913. *(15/-)*

95. The British Parasitic Copepoda. By Thomas and Andrew Scott. Vol. I (Copepoda parasitic on Fishes, Part I).—Text. xii + 256 pp., 2 plates. 8vo. 1913. *(15/-)*

For the Seventieth Year, 1913.

96. The British Parasitic Copepoda. By THOMAS and ANDREW SCOTT. Vol. II (Copepoda parasitic on Fishes, Part II).—Plates. xii + 144 pp., 72 plates. 8vo. 1913. *(25/-)*

For the Seventy-first Year, 1914.

97. The British Marine Annelids. By W. C. McINTOSH. Vol. III. Part I.—Text. Polychæta. Opheliidæ to Ammocharidæ. viii + 368 pp. Folio. 1915. *(25/-)*

For the Seventy-second Year, 1915.

98. The British Freshwater Rhizopoda and Heliozoa. By JAMES CASH and G. H. WAILES, assisted by JOHN HOPKINSON. Vol. III. The Rhizopoda, Part III. By G. H. WAILES. xxiv + 156 + 52 pp., 25 plates (xxxiii–lvii), and frontispiece. 8vo. 1915. *(12/6)*

99. The Principles of Plant-Teratology. By W. C. WORSDELL. Vol. I. xxix + 270 + 50 pp., 25 plates. 8vo. 1915. *(25/-)**

For the Seventy-third Year, 1916.

100. The British Marine Annelids. By W. C. McINTOSH. Vol. III. Part II.—Plates. viii + 48 pp., 24 plates. Folio. 1915. *(25/-)**

101. The Principles of Plant-Teratology. By W. C. WORSDELL. Vol. II. xvi + 296 + 56 pp., 28 plates (xxvi–liii). 8vo. 1916. *(25/-)*

For the Seventy-fourth Year, 1917.

102. The British Charophyta. By JAMES GROVES and Canon GEORGE RUSSELL BULLOCK-WEBSTER. Vol. I. Nitelleæ, with Introduction. xiv + 142 + 40 pp., 20 plates. 8vo. 1920. *(25/-)*

For the Seventy-fifth Year, 1918.

103. The British Freshwater Rhizopoda and Heliozoa. By JAMES CASH and G. H. WAILES, assisted by JOHN HOPKINSON. Vol. IV. Supplement to the Rhizopoda by G. H. WAILES and Bibliography by JOHN HOPKINSON. xii + 130 + 12 pp., 6 plates (lviii–lxiii). 8vo. 1919. *(12/6)*

104. The British Freshwater Rhizopoda and Heliozoa. Vol. V. Heliozoa. By G. H. WAILES. x + 72 + 24 pp., 11 plates (lxiv–lxxiv). 8vo. 1921. *(12/6)*

For the Seventy-sixth Year, 1919.

105. A Monograph of the British Orthoptera. By W. J. LUCAS. xii + 264 + 52 pp., 26 plates. 8vo. 1920. *(25/-)**

For the Seventy-seventh Year, 1920.

106. The British Marine Annelids. By W. C. McINTOSH. Vol. IV. Part I. Polychæta. Hermellidæ to Sabellidæ. viii + 250 pp., 15 plates. Folio. 1922. *(50/-)*

For the Seventy-eighth Year, 1921.

107. The British Marine Annelids. By W. C. McINTOSH. Vol. IV. Part II. Polychæta. Sabellidæ to Serpulidæ and additional species. With an Index to the whole work. xii + 289 pp., 14 plates. Folio. 1923. *(50/-)*

For the Seventy-ninth Year, 1922.

108. The British Desmidiaceæ. By W. and G. S. WEST. Vol. V. By NELLIE CARTER. With an Index to the whole work. xxi + 300 + 78 pp., 39 plates (cxxix–clxvii). 8vo. 1923. *(37/6)**

For the Eightieth Year, 1923.

109. The British Charophyta. By JAMES GROVES and Canon G. R. BULLOCK-WEBSTER. Vol. II. Chareæ, with concluding articles and Index. xii + 129 pp., 25 plates (xxi–xlv). 8vo. 1924. *(25/-)*

For the Eighty-first Year, 1924.

110. The British Hydracarina. By C. D. SOAR and W. WILLIAMSON. Vol. I. x + 216 + 40 pp., 20 plates. 8vo. 1925. *(37/6)*

For the Eighty-second Year, 1925.

111. Wilhelm Hofmeister: The Work and Life of a Nineteenth Century Botanist. By K. VON GOEBEL. Translated by H. M. BOWER and edited by F. O. BOWER. xi + 202 pp. Portrait and two facsimile letters. 8vo. 1926. *(12/6)*

For the Eighty-third Year, 1926.

112. The British Hydracarina. By C. D. SOAR and W. WILLIAMSON. Vol. II. viii + 215 + 40 pp., 20 plates (xxi–xl). 8vo. 1927. *(37/6)*

For the Eighty-fourth Year, 1927.

113. The British Sea Anemones. By T. A. STEPHENSON. Vol. I. xiv + 148 + 28 pp., 11 coloured and 3 black and white plates. 8vo. 1928. *(37/6)*

For the Eighty-fifth Year, 1928.

114. Further Correspondence of John Ray. By R. W. T. GUNTHER. xxiv + 332 pp. Portrait and two plates. 8vo. 1928. *(12/6)*

115. The British Hydracarina. By C. D. SOAR and W. WILLIAMSON. Vol. III. viii + 184 + 40 pp., 20 plates (xli–lx). 8vo. 1929. *(37/6)*

For the Eighty-sixth Year, 1929.

116. The Planktonic Diatoms of Northern Seas. By MARIE V. LEBOUR. ix + 244 + 8 pp., 4 plates. 8vo. 1930. *(12/6)*

For the Eighty-seventh Year, 1930.

117. The Aquatic (Naiad) Stage of the British Dragonflies. By W. J. LUCAS. xii + 132 + 70 pp., 35 plates. 8vo. 1930. *(25/-)*

For the Eighty-eighth Year, 1931.

118. The British Freshwater Copepoda. By R. GURNEY. Vol. I. lii + 238 pp. 8vo. 1931. *(25/-)*

For the Eighty-ninth Year, 1932.

119. The British Freshwater Copepoda. By R. GURNEY. Vol. II. ix + 336 pp. 8vo. 1932. *(25/-)*

For the Ninetieth Year, 1933.

120. The British Freshwater Copepoda. By R. GURNEY. Vol. III. xxix + 384 pp. 8vo. 1933. *(37/6)*

For the Ninety-first Year, 1934.

121. The British Sea Anemones. By T. A. STEPHENSON. Vol. II. xii + 426 + 38 pp., 8 coloured and 11 black and white plates. 8vo. 1935. *(37/6)*

For the Ninety-second Year, 1935.

122. A Monograph of the British Neuroptera. By F. J. KILLINGTON. Vol. I. xix + 269 + 30 pp., 4 coloured and 11 black and white plates. 8vo. 1936. *(25/-)*

For the Ninety-third Year, 1936.

123. A Monograph of the British Neuroptera. By F. J. KILLINGTON. Vol. II. xii + 306 + 32 pp., 4 coloured and 11 black and white plates. 8vo. 1937. *(25/-)*

For the Ninety-fourth Year, 1937.

124. The "Critica Botanica" of Linnæus. Translated by the late Sir ARTHUR HORT, Bt., M.A. Revised by Miss M. L. GREEN, B.A., F.L.S. xxvii + 239 pp. 8vo. 1938. *(12/6)*

125. Bibliography of the Larvæ of Decapod Crustacea. By ROBERT GURNEY, M.A., D.Sc., F.L.S. viii + 123 pp. 8vo. 1939. *(12/6)*

For the Ninety-fifth Year, 1938.

126. The Comity of Spiders. Vol. I. By WILLIAM SYER BRISTOWE, M.A., Sc.D.(Camb.), F.Z.S. x + 228 + 40 pp., 19 plates. 8vo. 1939. *(25/-)*

For the Ninety-sixth Year, 1939.

127. The British Water Beetles. Vol. I. By F. BALFOUR-BROWNE. xx + 375 + 12 pp., 5 plates. 8vo. 1940. *(25/-)*

For the Ninety-seventh Year, 1940.

128. The Comity of Spiders. Vol. II. By WILLIAM SYER BRISTOWE, M.A., Sc.D.(Camb.), F.Z.S. xiv + 332 + 8 pp., 3 plates. 8vo. 1941. *(25/-)*

For the Ninety-eighth Year, 1941.

129. Larvae of Decapod Crustacea. By ROBERT GURNEY, M.A., D.Sc., F.L.S. viii + 306 + 7 pp., 122 figs. 8vo. 1942. *(25/-)*

For the Ninety-ninth and One Hundredth Years, 1942 *and* 1943.

130. The Pleistocene Period: Its Climate, Chronology and Faunal Successions. By FREDERICK E. ZEUNER, D.Sc., F.Z.S., F.G.S. xii + 322 + 7 pp., 76 figs. 8vo. 1945. *(42/-)*

In Preparation.

The British Water Beetles. Vol. II. By F. BALFOUR-BROWNE.

Made and printed in Great Britain by
Adlard & Son, Ltd.,
at their works, Bartholomew Press, Dorking.